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LABORATORY ASSESSMENT OF THE CHANGES IN THERMAL PROPERTIES OF POLAR DIVING SUIT MATERIAL WHEN EXPOSED TO OILS AT LOW TEMPERATURES

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METRIC CONVERSION FACTORS

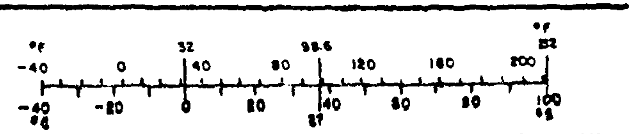
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

The U. S. Coast Guard is evaluating the use of divers under ice as one means of oil-spill surveillance in arctic and subarctic regions. The degree of thermal protection provided to the diver by presently approved suits, which are made of neoprene foam lined on one or both sides by nylon fabric, under the combined action of oil, water and frigid temperatures is not known. The present report describes the results of a laboratory study in which any changes in the thermal and physical properties of the suit material were assessed through systematic tests on small samples (12"X12") when they were kept immersed in various oils and oil-water mixtures at various temperatures (-4°C to +10°C) and periods of time (5 to 22 hours). Physical (length, volume, density) and thermal (conductivity) properties of the samples were measured before and after each test. The results show that, although the suit material performs well in general, under certain conditions the fabric lining as well as the foam absorb some oil and that this absorbed oil cannot be removed easily either by physical expression or by cleaning with commonly available detergents. The absorbed oil leads to some increases in density and in thermal conductivity, with the latter change for the "worst case" being about 35%.

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PREFACE

The present report is being issued as the final report of a study to "Conduct a Study to Determine Any Losses in Thermal Protection Provided by Polar Diving Suits When Exposed to Oil at Low Temperatures" performed by T.S. Associates, Incorporated under Contract No. DTCG23-80-C-20035 with the United States Coast Guard. Technical monitoring for the contract was provided by Dr. C. D. McKindra of the USCG.

The authors would like to express their special thanks to the following individuals and organizations for their cooperation during the program:

Mr. Bill Kerner of Parkway Fabricators, South Amboy, N. J. for providing many 12" X 12" samples of the suit material.

EPA-OHMSETT Facility, Leonardo, N. J. for providing 5 gallons each of Murban Crude oil and LaRossa Crude oil.

Howard Community College, Columbia, Md. for providing #2 Fuel oil and Steuart Petroleum Co. of Washington, D. C. for providing #6 Fuel oil.

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I. INTRODUCTION

The U. S. Coast Guard is presently evaluating the use of divers under ice as one means of oil-spill surveillance in arctic and subarctic regions. Since the thermal conductivity of water at $0^{o}C$ is nearly 25 times as much as that of air at the same temperature, a submerged diver faces loss of body heat in $0^{o}C$ water at a rate which is 25 times larger than that in $0^{o}C$ air. Therefore, providing adequate protection for the diver from hypothermia and other harzards of the cold is of vital importance when diving in a polar environment. A major limitation to a diver's performance in cold water is, indeed, the lack of adequate thermal protection.

The Coast Guard and the U. S. Navy have approved two diving suits for use in a cold environment; these are the Unisuit made by Poseidon Systems U.S.A., and the Supersuit made by O'Neil*. Both of the foregoing suits are made from a neoprene-foam material, approximately 1/4" thick and lined on one or both sides by a nylon fabric, manufactured by the Rubatex Corporation. The thermal conductivity of this neoprene foam (density $\backsim$15.1 lb/ft^3) is $\backsim$0.029 Btu/hr-ft-^{o}F, at a mean temperature of $75^{o}F$.[1] For comparison, air, at 1 atm pressure and $75^{o}F$ mean temperature, has a thermal conductivity of $\backsim$0.015 Btu/hr-ft-^{o}F.

According to Jenkins[2], the aforementioned variable-volume, dry suits provide 'superior' thermal protection to polar divers. However, the operating-instruction manual for the Unisuit states: "The Arctic undersuit is quite adequate for most conditions sport divers encounter; extended durations in extremely cold water may call for more protection". Furthermore, in any oil-spill surveillance in the arctic and subarctic regions, the presence of oil adds another dimension to the problem of providing thermal protection in the cold.

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*A telephone contact with O'Neil revealed, however, that this company has not manufactured any Supersuits for the past two years.

[1] Martorano, J. J., "Evaluation of Divers' Dress Suits in Maintaining Body Temperature in Cold Water," AD-265907, U. S. Naval Medical Field Research Laboratory, Camp Lejeune, NC, October 1961.

[2] Jenkins, W. T., "A Guide to Polar Diving," Naval Coastal System Center, Panama City, Florida, June 1960, p. 90.

It is not known, a priori, how the combined presence of oil, saline water and frigid temperatures may affect the physical properties or the degree of thermal protection provided by the suits, especially after repeated exposures. Moreover, diving suit sections containing cemented seams and metallic zippers may be more susceptible to any damage brought about by these adverse environmental conditions.

Based on the foregoing considerations, the Coast Guard desired an assessment of the changes, if any, in the degree of thermal protection provided by polar diving suits when they are exposed to oil at low temperatures. The present report describes the results of a laboratory study conducted by T.S. Associates, Incorporated to carry out the aforementioned assessment. In the study, any changes in the thermal and physical properties of the suit material were assessed through systematic tests on small samples (12" X 12") of the suit material in a specially-designed, compact, controlled-temperature environmental chamber.

Prior to the present study, the Coast Guard had already formulated a comprehensive test plan involving tests in which the suit material samples were immersed in oils alone and in combinations of oil-water mixtures for various periods of time, ranging from 5 to 22 hours, and at various temperatures, ranging from -4 to +10°C. The general objectives of the study as well as the detailed test plan are described in Section II of the present report. The test set-up as well as the experimental procedures are discussed in Section III, while the tests themselves, as well as the results, are presented in Section IV. Finally, some conclusions and recommendations are given in Section V.

II. OBJECTIVES, SCOPE AND TEST PLAN

The general objective of the present program was to assess any losses in the thermal protection provided by polar-suit materials when they are exposed to oil at low temperatures. The objective was to be accomplished through laboratory experiments, under controlled-temperature conditions, on 12" X 12" (30.5 X 30.5cms) sized samples of the suit material. Of specific interest were any changes in physical properties, such as length, thickness and density, as well as in the thermal conductivity. It was also desired to test some samples containing cemented seams and zipper sections, so as to assess whether the foregoing affect any losses in thermal protection. Five baseline oils were of interest, namely, #2 Fuel oil, #6 Fuel oil, SAE 40 oil, Thums Crude oil and Prudhoe Bay Crude oil*.

As noted earlier, prior to the present study the Coast Guard had developed a detailed test plan involving certain specific series of tests. In the present program, the tests were carried out at the conditions specified. Thus, in order to place the remainder of the report in perspective, the test plan is described in the present section. The test plan involved four separate test series, and each is described briefly below.

<u>Oil-Suit-Material Interaction Tests</u>

In these tests, the suit-material samples were required to be immersed in the test oils for a period of 22 hours, with the physical and thermal characteristics being measured before and after the tests.

<u>Variable-Temperature Tests</u>

In these tests, the suit-material samples were required to be immersed in oil-water (both fresh and saline) mixtures, of fifty percent by volume, at different temperatures ranging from -4°C to +10°C, with the temperatures being varied at 2°C intervals and with each temperature being maintained for a period of not less than five hours. For the "worst case" from the foregoing tests, the test was to be repeated for decreasing temperatures from +10°C to -4°C at the same temperature intervals and at the same intervals of time.

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*As discussed in Section III, samples of the two crude oils could not be obtained, at least in the small quantities that were desired. Hence two other equivalent crudes were substituted for them.

Cleaning Tests

The objective of this test series was to examine the effects of cleaning on the physical and thermal characteristics of the suit material. The suit material was required to be immersed at $0^{o}C$ in a mixture of the "worst case" oil from the previous test series and 35% saline water for a period of not less than five hours. The suit material was then to be cleaned with a typical soap, and any changes in properties determined. The cleaning cycle was to be repeated a minimum of three times.

Stretch Tests

The objective of this test series was to determine any additional effects due to the stretch that the material is subjected to as a result of the diver wearing it. The suit-material samples were to be immersed for a period of not less than five hours in the "worst case" oil-water mixture from the previous test series, while being subjected to a tensile force of known magnitude. The tests were to be repeated for several values of the force in order to determine typical expected changes.

Dynamic Tests

The objective of this test series was to investigate any effects of the dynamic cycles that the suit material may undergo due to repeated entries and reentries of the diver into the water. The effects of cyclic immersions and withdrawals of the suit-material samples from the oil-water mixture were to be assessed for the "worst case" combinations (under static conditions) of oil, saline water and cold temperature.

A test matrix listing the various tests involved is shown in Table 1.

TABLE 1 - TEST MATRIX

TEST SERIES	TEST FLUID	TEST TEMPERATURE °C	TEST TIME, HOURS
Oil-Suit Material Interaction	Prudhoe Bay Crude	0	22 hrs.
	Thums Crude	0	22 "
	SAE 40 oil	0	22 "
	#2 FUEL OIL	0	22 "
	#6 FUEL OIL	0	22 "
	Fresh Water	0	22 "
Variable Temperature	Prudhoe Bay Crude + fresh water (f.w.)	-4, -2, 0, 2, 4, 6, 8, 10	5 hrs. at each temp.
	Thums Crude + f.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	SAE 40 + f.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	#2 FUEL + f.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	#6 FUEL + f.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	Prudhoe Bay Crude + 35‰ saline water (s.w.)	-4, -2, 0, 2, 4, 6, 8, 10	"
	Thums Crude + s.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	SAE 40 + s.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	#2 FUEL + s.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	#6 FUEL + s.w.	-4, -2, 0, 2, 4, 6, 8, 10	"
	Worst of above	10, 8, 6, 4, 2, 0, -2, -4	"
Cleaning	Worst oil + s.w.	0	5 hrs.; repeat the cycle 3 to 5 times
Stretch	Worst condition from variable-temperature test series		5 hrs.; repeat the cycle 3 times with different stretch weights
Dynamic Effects	Worst condition from variable-temperature test series		5 hrs.; repeat the cycle 3 times with different cycling frequencies

III. TEST SET-UP AND PROCEDURES

In the present section we first give a description of the specially-constructed, controlled-temperature environmental chamber. The manner in which the samples are tested so as ensure that only the outside of the material is exposed to the oil is described next. A discussion of the techniques used to make the various relevant measurements is then given.

The Environmental Chamber

The test plan described in Section II calls for the testing of the 12" X 12" (30.5 X 30.5cms) suit-material samples at controlled temperatures ranging from $-4^{o}C$ to $+10^{o}C$. To this end, we had searched the product literature and had originally considered the use of a commerically-available, circulating water bath. Such baths are primarily used in a circulating mode, wherein the test fluid, which should be compatible with the bath system, is circulated through specially designed heating and cooling coils which are controlled by a sensitive temperature sensing element.

Our examination of the product literature and our discussions with manufacturers' representatives revealed, however, that the circulating systems of commercially-available baths would not be suitable for handling the quite viscous oils and oil-water mixtures that were to be used in the present tests. The foregoing difficulty could have been overcome by immersing a test container containing the desired oil or oil-water mixture into the circulating water bath, and by using in the bath only a fluid that is compatible with its circulating system. Cooling of the test fluid as well as the control of its temperature could have been accomplished by heat transfer between the test and circulating fluids through the walls of the container.

While the aforementioned solution appeared to be quite acceptable, an additional difficulty arose due to the limited sizes of the bath opening in commercially-available, off-the-shelf models. Thus, we chose to utilize in the present program a specially designed system which uses sensitive, temperature-control components (of the type used in off-the-shelf water baths) in conjunction with a sufficiently large test cell. Thus the test set-up we finally chose overcame the aforementioned difficulty of the limited sizes of conventional bath openings and even allowed us to conduct more than one test simultaneously, without sacrificing the temperature-control capability sought from a conventional water bath.

In the test set-up, one or more test cells, with the test fluids as well as the test samples inside them, were placed within the controlled-temperature of a simple, chest-type, household food freezer (K mart KMA80, 8 cu-ft model). In commercially-available water baths, both heating and cooling elements (as well as associated control equipment) are provided, since, in general, both temperatures above and below ambient may be of interest. However, since the temperature range of $-4^{o}C$ to $+10^{o}C$ of interest herein lies well below the normal laboratory temperatures, our initial experiments soon revealed that a heating element was unnecessary in our set-up and that the required test fluid temperatures could be maintained (due to the normal warming of the freezer compartment when the freezer is shut off) simply by regulating the freezer's on-off cycle by a precision temperature controller (YSI model 63RC with measuring probe YSI model 631). The temperature controller can be set at any desired value, and the temperature of the test fluid can thus be expected to be maintained to a very good accuracy at a specified value.

Several preliminary tests were conducted to verify the degree of temperature control provided by the foregoing simple arrangement. Apparently because of the fact that the cooling of the freezer compartment progresses from the bottom up, our initial temperature measurements with thermocouples placed at different depths inside relatively deep test containers ($\sim$18" deep) revealed a vertical temperature gradient of as much as $0.2^{o}C$/in. in the bottom of the test fluid. Although the foregoing feature seemed to imply that a circulation system such as that used in commercial water baths may be necessary to achieve a reasonable uniformity of the test-fluid temperature, further tests showed that when the test suit-material sample was placed horizontally on its side in the test fluid in a relatively shallow container ($\sim$5" deep) it would not be subjected to more than $\sim 0.2^{o}C$ temperature differential.*

*Since the temperature range of interest herein includes the temperature at which water has its maximum density (namely, $4^{o}C$), some anomalous temperature stratification patterns were noted in the tests. Thus it was found that in the temperature range from $0^{o}C$ to $4^{o}C$, the temperature of the test fluids at the bottom of the test container was actually somewhat <u>higher</u> than that at the top!

Thus the final test set-up used in the present program consisted of heavy-duty plastic pans that contained the test fluid and the test suit-material sample immersed* in the fluid, with the pans being placed inside the freezer compartment. The controller probe, which is immersed directly in the test fluid, controls the on-off cycle of the freezer. The foregoing arrangement also enabled us to carry out more than one test simultaneously (of course, with different oils or for different types of samples). Thirty gauge, teflon-insulated, copper-constantan thermocouples, which were placed in the test fluids, allowed the continuous monitoring of the test-fluid temperatures; see Fig. 1.

In summary, the relatively simple set-up described above not only gave the desired accuracy of temperature control, but also allowed the large number of tests involved in the program to be performed rapidly and efficiently. For example, as can be seen from Table 1, the task on variable-temperature effects involved eighty-eight separate tests, comprising different oil-water-temperature combinations, with the tests to be performed every five hours! It is clear that performing these tests one at a time in commercially available baths would have been highly impractical and inefficient. On the other hand, the test set-up we have described enabled five different test fluids (and test samples) to be tested simultaneously, thus considerably facilitating the performance of the experiments.

<u>Test Fluids</u>

The test plan described in Section II calls for the use of five base oils, namely, #2 Fuel oil, #6 Fuel oil, SAE 40 oil, Prudhoe Bay Crude oil and Thums Crude oil. While we were able to locate <u>local</u> sources for the first three oils and to obtain them readily, we were unable to obtain samples of the two crude oils. Inquiries we made with various local dealers, with major oil companies such as British Petroleum, Union Oil Co. of California, Sohio, Sun Oil Company, etc., as well as with EPA's OHMSETT facility were all unsuccessful in terms of being able to obtain small samples of the two crude oils.

Personnel at EPA's OHMSETT facility did, however, provide us with samples of two other crude oils, namely Murban Crude oil and LaRossa

*Because of its buoyancy, the foam sample tends to rise, and is held immersed below the oil surface by a retaining mechanism clamped to the edges of the pan. The buoyancy of the foam also ensures that it does not simply "lie" on the bottom and that <u>both</u> outside surfaces of the folded sample are exposed to the oil.

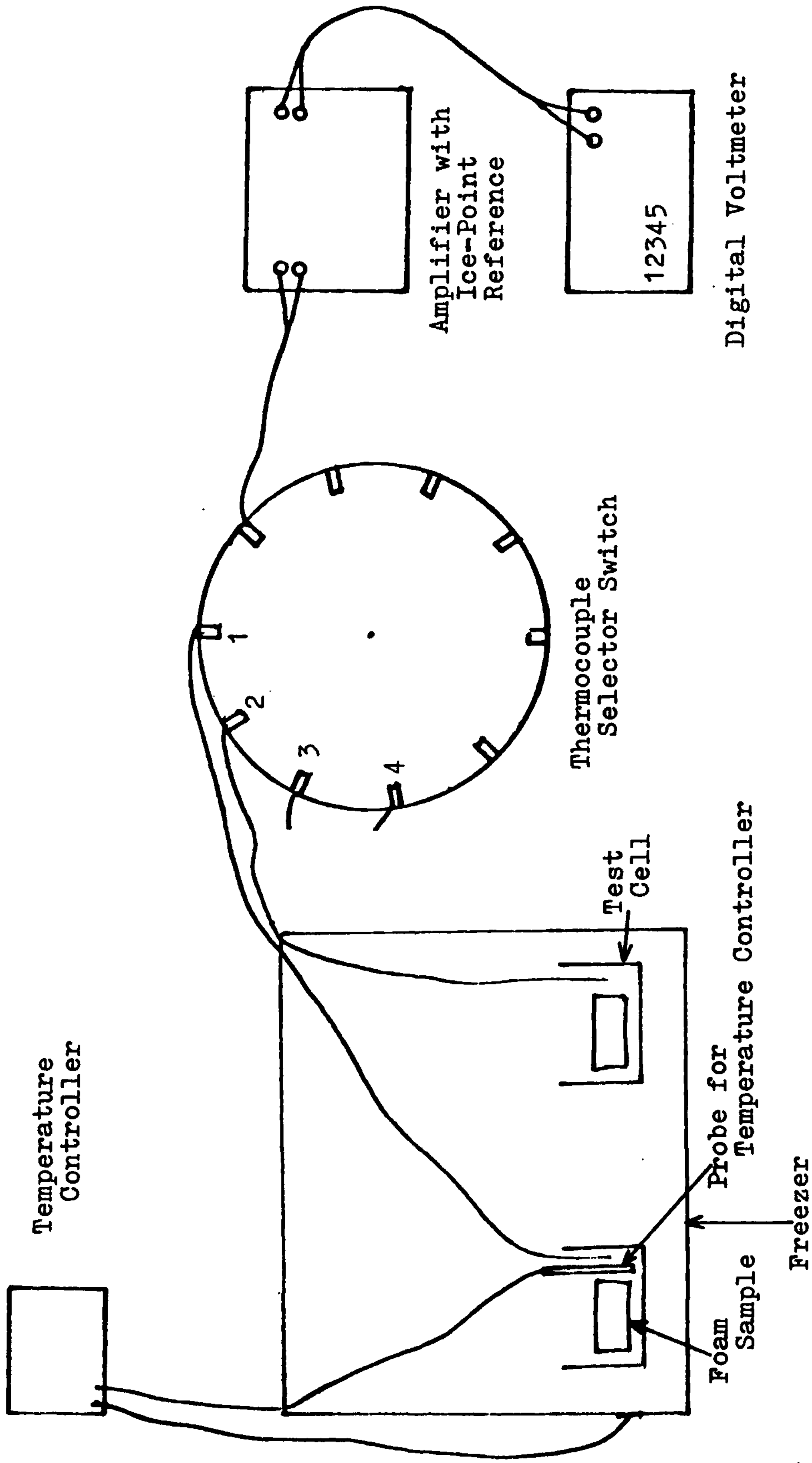


FIGURE 1 - TEST SET-UP

Crude oil. It should be noted that LaRossa Crude has a viscosity of about 340 centistokes at 0^oC, which is in the same range as that of Prudhoe Bay Crude, and that Murban Crude has a viscosity of about 10.5 centistokes at 0^oC, which is not very different from that of Thums Crude oil (23 to 60 centistokes). Thus, the tests described in Section IV of the present report were done with the latter two crudes rather than those listed in Section II.

Sample Preparation

As already noted, in order for the laboratory tests on the 12" X 12" samples to be representative of field conditions, only the outside of the suit material should be exposed to the oils and to the oil-water mixtures. In the majority of the tests, the foregoing requirement was assured simply by folding the samples in half and by firmly clamping (using C-clamps) the three free edges between two [-shaped wooden strips. The two [-shaped wooden strips of each "pressure seal" were wrapped around with a heavy-duty plastic sheet, which in turn was stitched together in such a way as to form a narrow pocket in between the [-shaped strips, thus enabling easy insertion and removal of the folded samples (see Fig. 6).

For the stretch tests, the foregoing procedure was unsatisfactory, since a uniform tensile force cannot be applied easily to a folded sample. Therefore, for this case two separate sample pieces were laid on top on each other and with their inside surfaces facing each other. The samples were first glued along the edges with neoprene cement, and, as an additional assurance of tight sealing, were stitched together using a heavy-duty sewing machine employed in shoe repairing. The actual manner in which the tensile load was applied to the sample is described in Section IV.

In passing, it may be mentioned here that a considerable amount of time and effort was spent to achieve a satisfactory seal, and to ensure that only the outside surface of the material came in contact with the oil. Chemical-sealing techniques, using a variety of adhesives (including the Unisuit cement obtained from Poseidon System, Inc.) and using various impermeable bonding surfaces (including different types of plastic sheets and aluminum foil) not only gave a poor, unsatisfactory seal, but also left adhesive coatings and pieces of the bonding surfaces on the sample (thereby complicating the measurements of the changes in density).

Density, Volume and Elongation Measurements

Any changes in the length (width) were measured with a vernier caliper (SGA M-1475-3) offering a reading accuracy of 0.008". Changes in the sample thickness were measured with a micrometer (SGA M-1510) offering a reading accuracy of 0.001". Changes in thicknesses of the suit-material samples were quite difficult to measure, however, because of the flexible nature of the suit-material samples. At the end of each test series, an attempt was made to measure the net change in the sample thickness accurately by placing the sample between two stiff acrylic plates and by subtracting the thicknesses of the plates from the measured values.

Density measurements were performed by the water-displacement method, wherein the test samples were placed in a graduated cylinder that was floating in a water container. The difference in the water displacements with and without the sample is a direct measure of the mass of the sample. The density was then calculated by dividing this mass with the measured volume of the sample.

Thermal Conductivity Measurements

In general, the thermal conductivity of any material can be determined readily by applying a known, steady heat flux to one side of a thin sample of the material and by measuring the temperatures on both sides of the sample. Since the temperature gradient across the thin sample is given, to a good approximation, by the ratio of the temperature difference between the two faces of the material and the thickness of the material, the thermal conductivity can be determined simply by dividing the known heat flux by the calculated temperature gradient. In practice, the heat flux can itself be measured by sandwiching the sample between two plates of a material of known conductivity. Then, since the heat flux must also be equal to the product of the thermal conductivity of the reference plates and the temperature gradient across either one of them, the heat flux can be determined if the temperature difference across the plates is measured.

The foregoing simple principle, as well as a modification of it, were used in the present program to determine the thermal conductivities of the suit-material samples before and after they were immersed in various oil-water mixtures. A schematic depiction of the arrangement used, which we have termed the TCM Box, is shown in Fig. 2. The TCM Box consisted of an approximately 12" X 12" X 12" cubical box with its four vertical surfaces made of wood and with one 12" X 12" X 1"-thick plexiglass plate, snugly fitted at the top, forming the upper surface of the box. The suit-material sample whose thermal conductivity was to be measured was held sandwiched between the aforementioned plexiglass plate and another of equal size placed on top of it. The necessary heat flux was supplied by four 40-watt, appliance-type light bulbs. The magnitude of the heat flux was controlled by controlling, by the use of a "dimmer" switch, the power input to the bulbs. Several layers of window-wire screening and aluminum foil were placed between the bulbs and the lower plexiglass plate to assure a uniform distribution of heat to the latter.

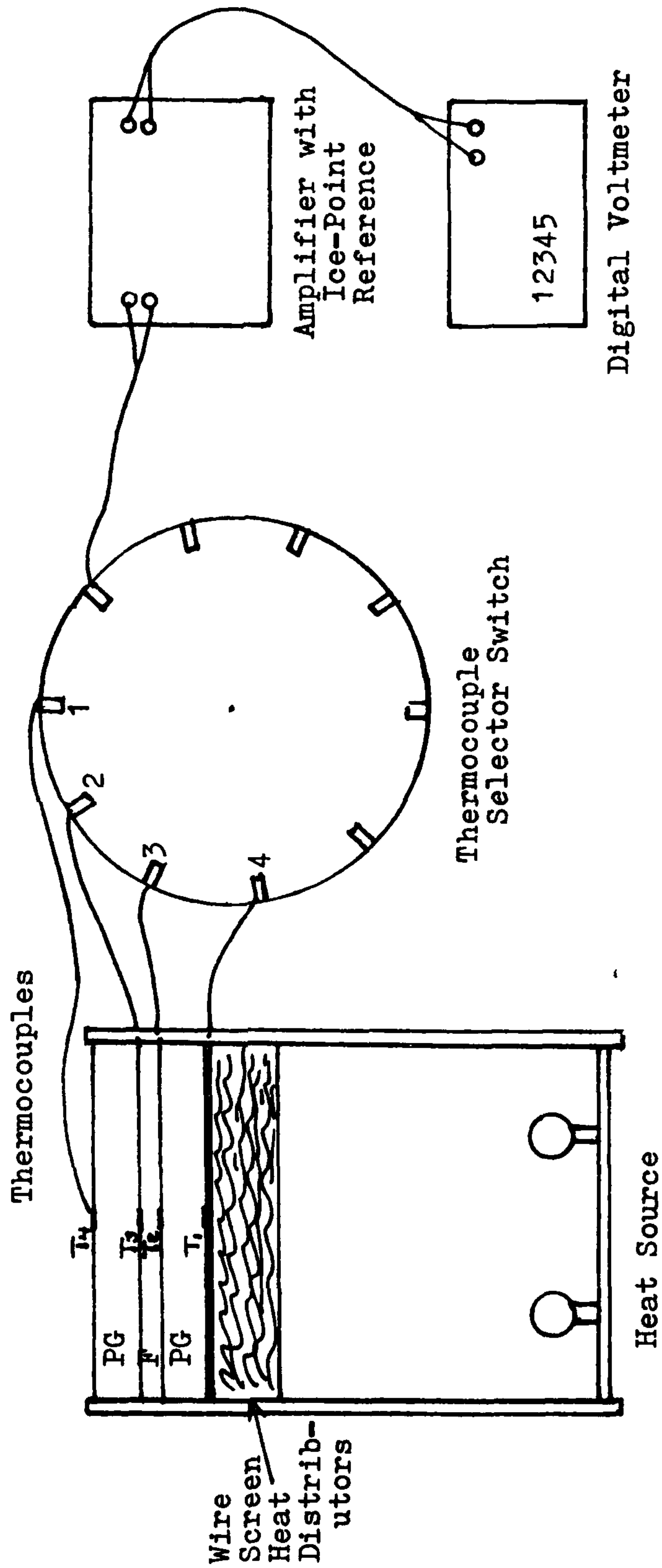
Attached to the centers of either sides of both plexiglass plates were four 30-gauge, copper-constantan thermocouples (Omega Style III, cement-on thermocouples*). The thermocouple leads were connected through a thermocouple selector switch (Omega OSW3-10) to an amplifier with a built-in, ice-point reference (Omega Omni-Amp II B model). The output from the amplifier was read directly with a digital millivoltmeter (Valhalla Scientific Model 4440).

Now, if a steady heat flux, q, is maintained normal to the surfaces of the plexiglass and the suit material, then (see Fig. 2 for notation),

$$q = \frac{k_{pg}}{t_{pg}} (T_1 - T_2) = \frac{k}{t} (T_2 - T_3) \qquad (1)$$

where k and k_{pg} are, respectively, the thermal conductivities of the suit material and the plexiglass, and t and t_{pg} are the corresponding thicknesses.

*These copper-constantan (ANSI symbol T) thermocouples, with a positive copper wire and a negative constantan wire, are recommended for use in mildly oxidizing and reducing atmospheres, and are suitable where moisture is present. As compared to other metal wires, these thermocouples offer greatly reduced errors due to inhomogeneity of the wires in zones of temperature gradients. The Omega style III thermocouple is constructed from 30-gauge, 0.01 inch diameter, bead-welded, standard limit of error thermocouple wires and has a response time of 0.3 seconds.



PG 12" X 12" X 1" Plexiglass Plates

F 12" X 12" X 0.25" Foam Samples

FIGURE 2 - SCHEMATIC OF THERMAL CONDUCTIVITY MEASUREMENT

From Eq (1)

$$k = \frac{k_{pg}}{t_{pg}} \cdot t \left(\frac{T_1 - T_2}{T_2 - T_3} \right) = C \cdot t/R \ , \qquad (2)$$

where

$$C = \frac{k_{pg}}{t_{pg}} = \frac{0.108}{0.0833} \approx 1.296 \ \text{Btu/hr-ft}^2\text{-}^{o}\text{F}$$

and

$$R = \frac{T_2 - T_3}{T_1 - T_2} \quad .$$

Note that, since k_{pg} ($\sim$0.108 Btu/hr-ft-^{o}F) is approximately four times as large as k ($\sim$0.029 Btu/hr-ft-^{o}F), use of 1" thick plexiglass plates should result in nearly equal temperature differentials across the plexiglass plates and the 1/4"-thick suit material. This means that an error of 0.01^{o}F in the temperature measurements for a 10^{o}F temperature differential (ie. T_1-T_2 = T_3-T_4 = 10^{o}F) will cause a maximum of 0.4% error in the thermal conductivity, k, of the suit material. However, since the error in the temperature measurement is of a random nature, the actual error in k should be much less than the above value.

The foregoing equations apply when a steady state exists; that is when the heat flux as well as the temperatures T_1, T_2, T_3 and T_4 are all independent of time. In general, however, immediately after the lamps in the TCM Box are turned on, or after a new sample is placed between the two plexiglass plates, conditions will not be steady, and a finite interval of time has to elapse before a reasonable approximation to steady-state conditions are reached. To illustrate the foregoing feature the variation of R with time after the power in the TCM Box is turned on is illustrated in Fig. 3 for a virgin suit-material sample. As the lamps are turned on, T_1 will begin to increase, but T_2 will still be approximately equal to T_3, so that R will initially be equal to zero. With increasing time, T_1, T_2 and T_3 will all begin to increase and hence also will the value of R. It can be seen from Fig. 3 that even after the elapse of 150 minutes,

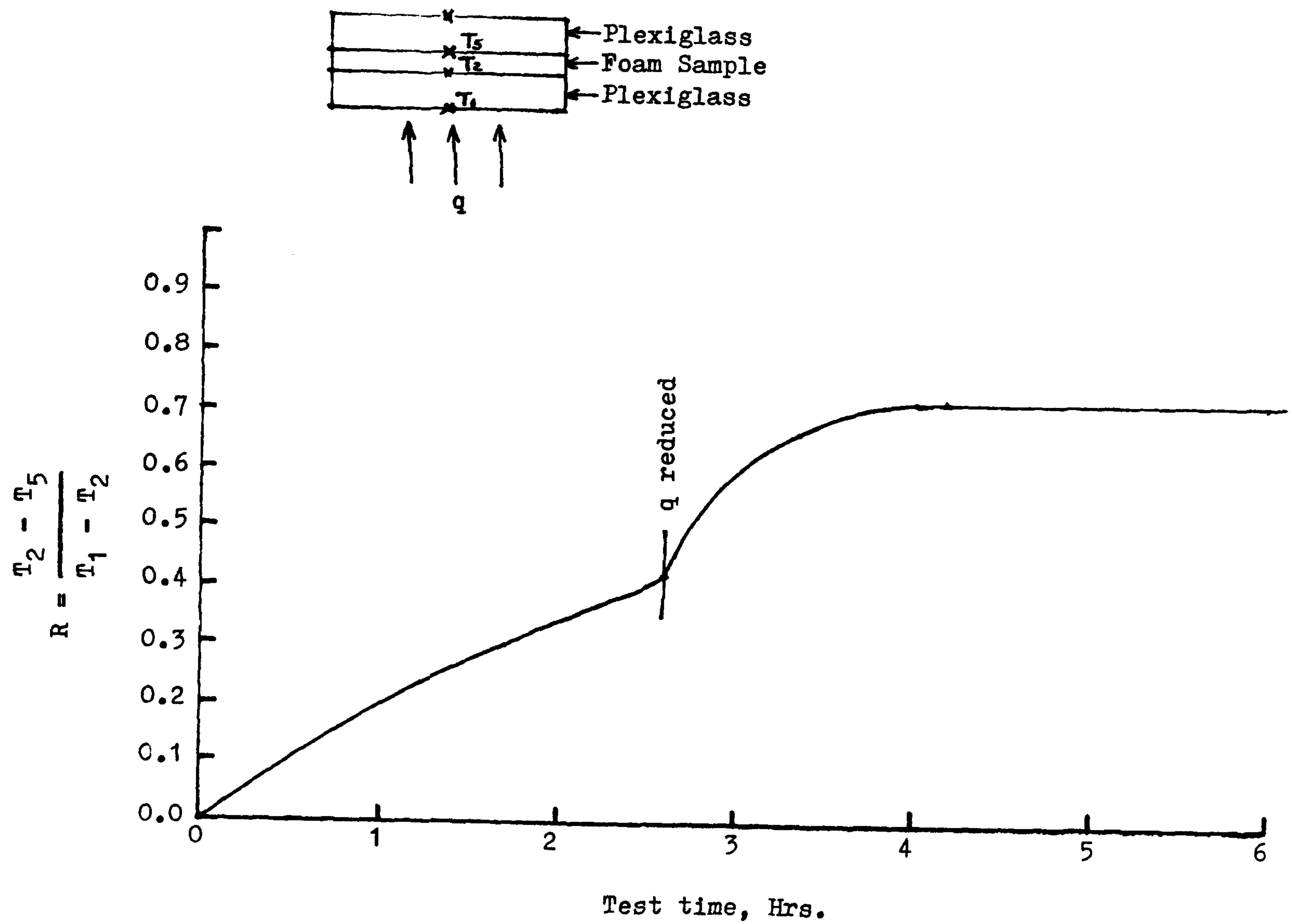


FIGURE 3 - R VERSUS TIME FOR VIRGIN SUIT-MATERIAL SAMPLE

R had not reached a steady-state value, although it appears to be asymptotically reaching such a state. At this point, the power input to the system was reduced; as can be seen from the figure, this action appears to speed-up the approach to a steady state. Finally, after nearly four hours, R does reach a steady-state value. The extended transient response just noted is, of course, a direct consequence of the fact that the 1"-thick plexiglass and the suit material are both very good insulators and that the temperatures T_2 and T_3 respond only slowly to changes in the temperature T_1.

The foregoing "steady-state technique" of measuring thermal conductivity is both simple and quite accurate, albeit time comsuming. The degree of accuracy that can be achieved is dependent on the accuracy to which the temperatures can be measured and on the degree of accuracy in the known, "reference" value of the thermal conductivity of the plexiglass. Indeed, when only <u>changes</u> in the thermal conductivity are of interest, as is the case herein, even a knowledge of the thermal conductivity of the plexiglass is unnecessary.

In the present study, the "steady-state" technique was used in the tests on the assessment of oil-suit-material interactions (see Section II), since in these tests measurements are made only after 22 hours of immersion of the samples in the oils. However, in the test series involving the effects of variable temperatures, a very large number of tests are involved. As already noted, in the later tests <u>five</u> oils were tested simultaneously, with the conductivity measurements for each case being required once every five hours. Clearly, for the foregoing case, a measurement technique which requires several hours to complete is unsuitable. Therefore, it was necessary to modify the "steady-state" technique, so as to enable measurements to be made before a steady state is reached. Before discussing the features of the latter, "unsteady technique", it is first appropriate to consider certain general principles of heat transfer.

Consider the time evolution of the temperature profile in a conducting medium of finite thickness and of infinite lateral extent, due to a heat flux through one of the surfaces. If it is assumed that the temperature throughout the material is initially uniform, then the temperature profiles will, at different times, be as shown in the sketch below, and will be described by complementary error functions (since these functions are the solutions of the classical heat conduction equation). At any time t, the distance (from the

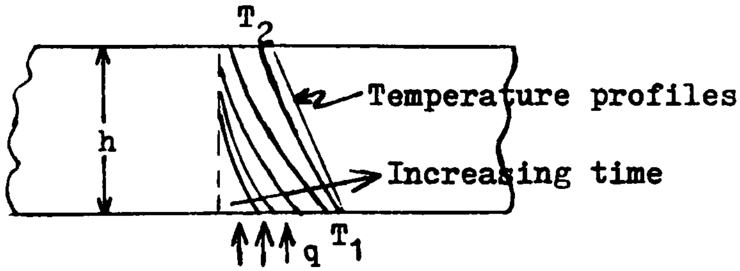


FIGURE 4 - SCHEMATIC REPRESENTATION OF THE TIME EVOLUTION OF TEMPERATURE PROFILES

bottom surface) over which the effect of the heat flux is felt is given by $Z \sim \sqrt{\kappa t}$ where κ is the thermal diffusivity of the material, expressed as $\kappa = k/\rho C_p$ with k being the thermal conductivity, ρ the density of the material and C_p as its specific heat.

An alternate way of viewing the aforementioned feature is that $\sqrt{\kappa t}$ represents the length scale characterizing the leading (linear) term in the power series expansion of the error function. Thus, in a material of thickness h, the temperature profile will be essentially linear at times which are large compared to h^2/κ. At these times we simply have

$$q_1 = k \frac{T_1 - T_2}{h}$$

This equation is indeed the approximation that has been used in the steady-state technique.

The TCM Box described earlier has two 12" X 12" X 1" thick plexiglass plates sandwiching the foam sample. It can be seen that the characteristic time scale for a 1" thick plexiglass plate ($k \approx 0.108$ Btu/hr-ft-^oF, $\rho_{pg} \approx 74.3$ lbs/ft^3 and $C_{pg} \approx 0.35$ Btu/lb-^oF) is

$$t^* = \frac{\rho_{pg}\ C_{pg}\ h^2}{k_{pg}} \approx 100 \text{ minutes}$$

Since, as noted earlier, a large number of tests (88 in all) are involved, requiring five thermal conductivity measurements at the end of each five-hour test interval, it became obvious at the outset that the 1"-thick plexiglass plates (which, as seen above, require time scales of the order of one hundred minutes or more to reach "steady state" conditions) were unsuitable for the variable temperature tests. Moreover, since the characteristic time scale is proportional to the square of the material thickness, it was also obvious that a reduction in the thickness of the "reference" plates (sandwiching the suit material) would lead to a significant reduction in the characteristic time scales. Therefore, the 1"-thick plexiglass plates were replaced by 12" X 12" X 0.1"-thick acrylic plates. Also, in order to relax the requirement of a "steady state" operation, the heat balances were recomputed, as shown below.

Consider the heat balance in a three-layer system in which the suit-material sample is sandwiched between two thin acrylic plates as shown schematically below.

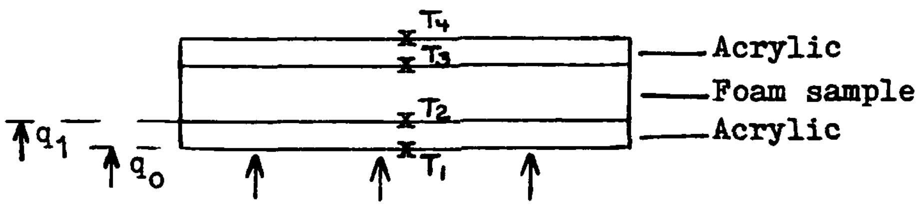


FIGURE 5 - SCHEMATIC REPRESENTATION OF HEAT BALANCE

Then a simple heat balance for the lower acrylic plate requires that $q_o = q_1$ + heat "stored" in the lower acrylic plate $= q_1 + q_s$. We assume a simple "forward-differencing" approximation of the form,

$$q_o = k_a \frac{T_1 - T_2}{h_a} \tag{3}$$

and

$$q_1 = k_f \frac{T_2 - T_3}{h_f} \tag{4}$$

Also, we can write

$$q_s = (\rho C_p h)_a \frac{d}{dt} \left[\frac{T_1 + T_2}{2} \right] \tag{5}$$

where subscripts a and f refer to the acrylic and to the foam respectively. It follows that

$$k_a \frac{T_1 - T_2}{h_a} = k_f \frac{T_2 - T_3}{h_f} + (\rho C_p h)_a \frac{d}{dt} \left[\frac{T_1 + T_2}{2}\right] \tag{6}$$

For known values of h_a, h_f and ρ_a, by measuring T_1, T_2 and T_3 at <u>two different times</u>, Eq (5) can be written as

$$k_f = a\, k_a - b\, C_{pa} \tag{7}$$

and

$$k_f = c\, k_a - d\, C_{pa} \tag{8}$$

Although, both k_a and C_{pa} are unknown, a priori, they can be determined by conducting a test with a virgin sample of the suit material and by solving Eqs (7) and (8) simultaneously for k_f = 0.029 Btu/hr-ft-^oF (a value for neoprene foam quoted by Rubatex Corp.). This gives C_{pa} = 0.27 Btu/lb-^oF and k_a = 0.0336 Btu/hr-ft-^oF. Thus Eq (6) yields

$$k_f = 0.089 \frac{T_1 - T_2}{T_2 - T_3} - \frac{1.769 \times 10^{-3}}{T_2 - T_3} \frac{d}{dt} \left[T_1 + T_2\right] \tag{9}$$

This is the equation used to determine k_f values in the tests. Note that t_a^* for a 0.1"-thick acrylic plate is about 3 minutes and that t_a^* for the foam sample is about 4 minutes. In all the tests, an initial period of at least 8 minutes was allowed after the foam was replaced between the acrylic plates and before the temperature measurements were made. In the measurements, the values of T_1, T_2, T_3 and T_4 were read-off the DVM at 2-minute intervals, and Eq (9) was used to compute k_f.

<u>Test Procedures</u>

Before a specific sample of the suit material was tested, its mass was determined using the water-displacement method and its thermal conductivity was also measured. To enable measurement of any changes in length or width of the sample, two sets of marks approximately 4" apart and at right angles to each other, were placed on the inside surfaces of the samples. (Our early experiments revealed that any marks placed on the outside surface of the sample were quickly erased by the oils.) The thickness of the virgin sample was measured using a micrometer.

After the foregoing measurements, the sample was folded and three of its unfolded edges were firmly clamped together (according to the procedure already described), so that only one side of the sample was exposed to the test fluid, when immersed in it. Once the test fluid (in the plastic container within the freezer compartment) attained the desired test temperature, the pressure-sealed sample was kept immersed in it for the desired period. During this interval the test fluid temperature was monitored using thermocouples, and was adjusted as and when necessary.

At the end of the test period, the plastic container with the sample was removed from the freezer. The sample was then lifted out of the test fluid (see Fig. 6), and the excess oil was allowed to drain off. The sample was then removed from the pressure seal (Fig. 6 shows an empty pressure seal in the foreground), and the superficial oil on its surface was removed gently using a knife-edged scraper. Any additional oil was also removed by gentle expression, and by toweling off with absorbent paper toweling.

The mass of the sample was then determined and the distances between the hatch marks on the back of the sample were measured. Finally, the thermal conductivity of the sample was measured using the TCM Box.

Summary

The test procedures and apparatus that were developed for the present program were both simple and accurate, and enabled a large number of tests to be performed speedily and efficiently. The test results themselves are described in the following section.

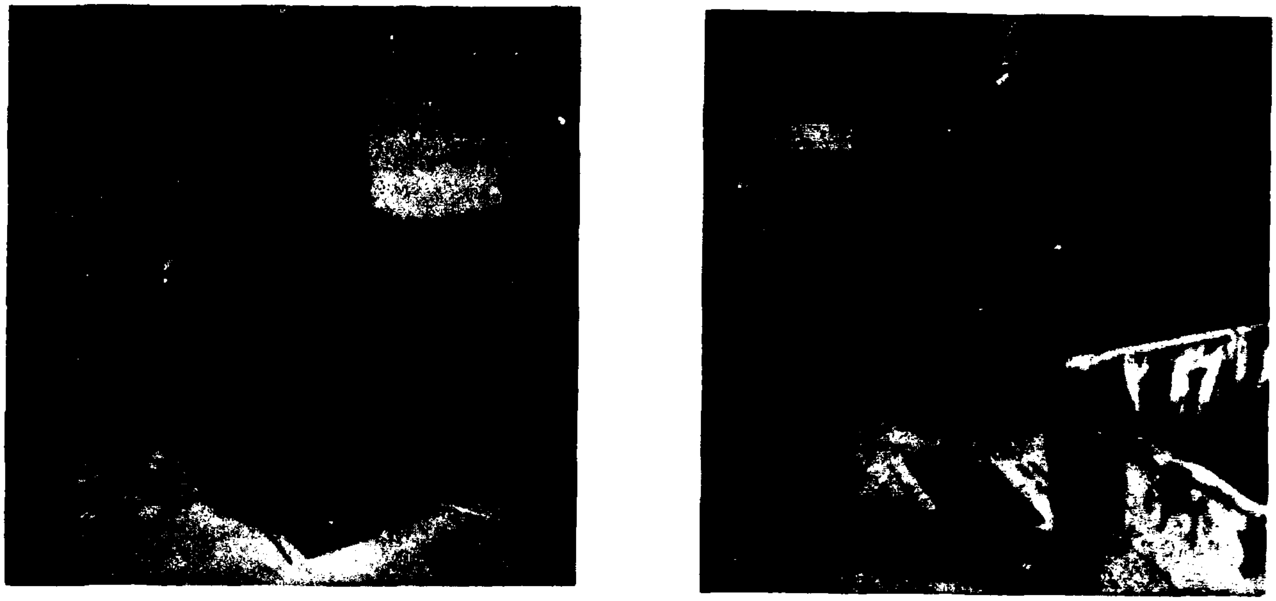


FIGURE 6 - TEST PROCEDURE

Photographs illustrate the procedure used in removing the suit-material samples from the oil-water mixtures. Note that an empty pressure seal is visible in the foreground in the photograph on the right.

IV. TEST RESULTS

The various series of tests and the corresponding results are described in the present section. The tests described herein correspond to the test plan given in Section II.

Oil and Suit-Material Interaction Tests

In these tests, the suit-material samples were immersed at 0°C for 22 hours in the five different oils already mentioned and in water. Any changes in physical properties (thickness, length, density) and in thermal conductivity were assessed by comparing the values before and after the controlled immersion.

The test results are shown in Table 2. The R values for the samples are also shown plotted in Fig. 7. In general, there were little or no changes in either the length or the thickness of the foam. However, there is a substantial change in the density of the sample due to absorption of the test fluid by the sample. A major portion of the oil appears to be absorbed into, and to remain on, the outer nylon fabric, since inspection of the unexposed surface of the sample (and its ends) does not reveal any signs of oil penetration through the neoprene foam itself. It should be noted that high-viscosity oils, such as LaRossa Crude and #6 Fuel oil, did not drain off easily even when the sample was hung out for 45 minutes, and that, as mentioned earlier, the superficial film of oil remaining on the surface had to be removed gently with a knife-edge scraper and by expression. Had the foregoing procedure not been used, observed changes in mass would have been even larger. Thus, the mass changes and, hence, the density changes, that we have reported, should be viewed with some caution.

As expected, all the test results show an increase in the thermal conductivity as compared to that of the virgin suit material. The #6 Fuel oil and the SAE 40 oil show an increase of ~14%, while the remaining three oils indicate an increase of less than 4%. (In Table 2 the thermal conductivity is also shown expressed in CLO units.) The test with water shows the largest increase, about 34%, in the thermal conductivity value. It should be noted that, after the sample from the water immersion test was placed between the two plexiglass plates of the thermal conductivity measurement box, a part of the

TABLE 2

RESULTS OF THE OIL-SUIT-MATERIAL INTERACTION TEST SERIES

Test Number	1		2		3		4*		5		6		7	
Test Fluids	#2 Fuel Oil		Murban Crude		LaRossa Crude		Murban Crude		Water		#6 Fuel Oil		SAE 40	
1 and 2 refer to before & after test conditions	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Sample thickness, t inches														
Diameter of inscribed circle, d inches	$4\frac{3}{32}$	$4\frac{5}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$
Water Displacement without the sample, D cc							690							
Water Displacement with the sample, D cc	870	930	870	895	875	900	850	875	875	890	860	885	860	890
Thermal Conductivity, R value	0.83	0.79	0.72	0.71	0.72	0.71	0.82	0.79	0.82	0.61	0.73	0.64	0.73	0.64
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$	0.015		0.0		0.0		0.0		0.0		0.0		0.0	
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$	0.011		0.0		0.0		0.0		0.0		0.0		0.0	
Mass Change $\frac{\Delta m}{m} = \frac{D_2 - D_1}{D_1 - D}$	0.333		0.139		0.135		0.156		0.081		0.147		0.176	
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$	0.322		0.139		0.135		0.156		0.081		0.147		0.176	
Thermal Cond. Change $\frac{\Delta k}{k} = \left(\frac{t_2}{t_1}\right)\left(\frac{R_1}{R_2}\right) - 1$	0.031		0.014		0.014		0.038		0.344		0.141		0.141	
Insulation in CLO units	0.826		0.857		0.857		0.837		0.646		0.761		0.761	

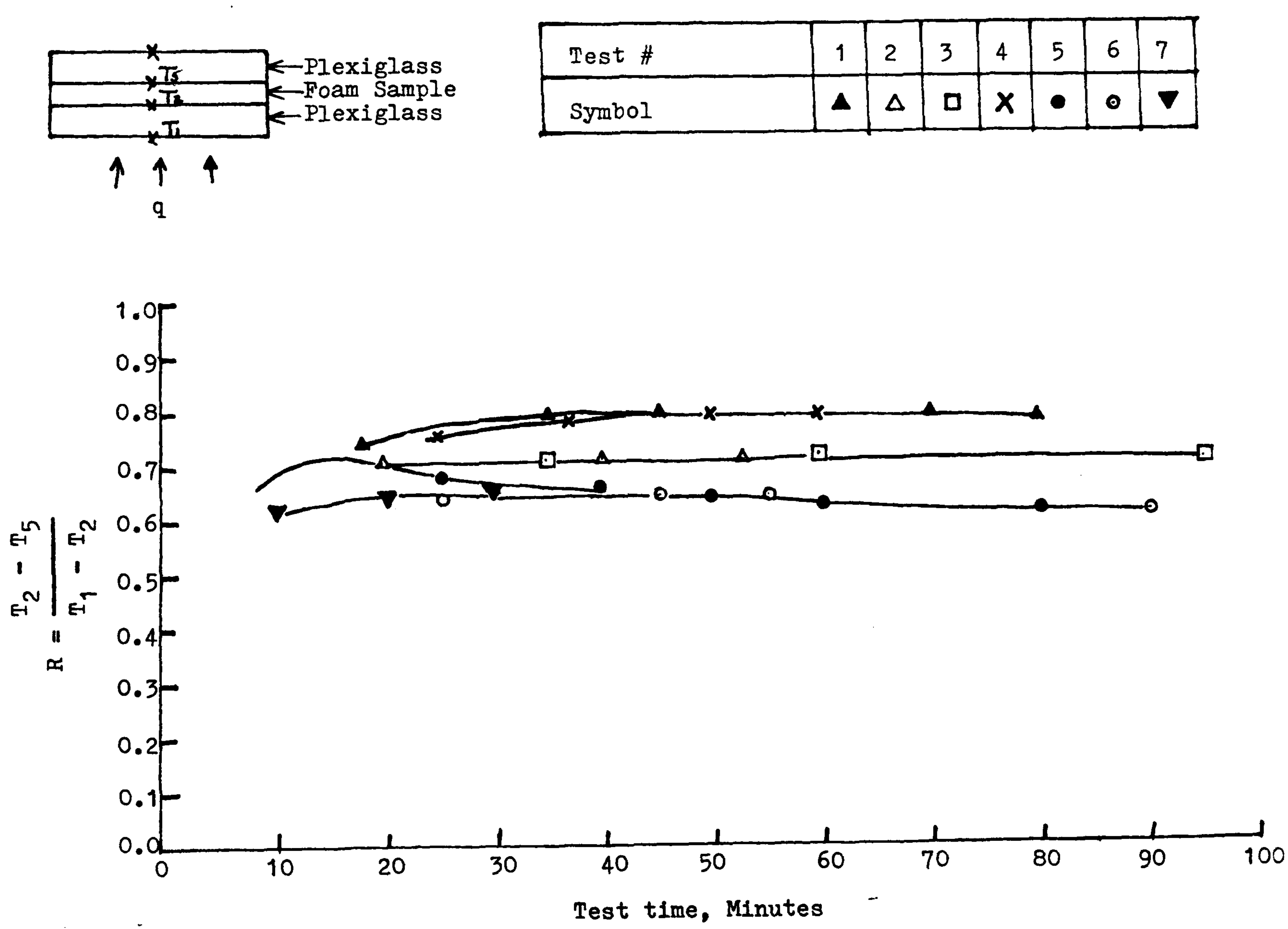


FIGURE 7 - R VERSUS TIME FOR TESTED SUIT-MATERIAL SAMPLES

water absorbed during the immersion tests was being driven off as its temperature rose; this water formed a thin vapor layer on the bottom surface of the upper plexiglass plate. It is likely that the measured value of the thermal conductivity was influenced by the foregoing phenomena. Of course, no attempt was made in the tests to dry the samples before measurements of thermal conductivity were made. How much of the water or of the absorbed oil should be removed by scraping, expression, drying, etc., is open to argument, and is to a large extent subjective. In our tests we have, however, tried to be consistent in the degree of removal in all cases. A more definitive resolution of the foregoing aspect will probably require in-situ measurements; that is, measurement of the changes in thermal conductivity while the samples are still immersed in the test fluids.

The foregoing test series also involved a test with a suit-material sample containing a seam. Comparisons of results for tests #2 and #4 suggest that the change in the thermal conductivity value for a sample with a seam is not very different from that for a seamless sample.

Variable Temperature Tests

In this test series, the test fluids consisted of mixtures of oil and either fresh water or 35‰ salt water in a 50:50 ratio by volume. The five base oils used herein were the same as those used in the previous test series, namely 1) LaRossa Crude, 2) Murban Crude, 3) SAE 40, 4) #2 Fuel and 5) #6 Fuel oil. The oil-water mixtures were prepared by blending, in batches, 16 ozs. of oil and 16 ozs. of water (either fresh or 35‰ salt water) at the lowest 'whip' speed on a Waring (8-speed, Futura II) blender for a period of five minutes. It should be noted here that although all the emulsions were very homogeneous to begin with, as the test progressed, some of the oil and water tended to separate from the uniform emulsions; in particular, much of the #2 Fuel oil had come out of the emulsion by the time the tests were completed.

It is relevant to point out again herein that as compared to only five tests in the previous test series, the present test series involved a total of 88, 5-hour tests (11 different test fluids and samples, each tested at 8 different temperatures). These tests were carried out in three separate groups. The first group consisted of tests with the five oil-fresh-water mixtures, while the second group consisted of tests with the five oil-saline-water mixtures. The third group consisted of a series of eight tests, at decreasing temperatures, with a new sample and the "worst case" oil-water mixture as determined from the previous two groups of tests.

In the first and second groups of tests, five different containers containing the different oil-water mixtures and the suit-material samples were placed inside the freezer compartment. The test temperatures were increased from -4°C to +10°C at 2°C intervals, with the test fluids being maintained at each test temperature for a period of not less than five hours. At the end of each test interval, the samples were removed, one after the other, from the oil-water mixtures, any superficial fluid on the samples was scraped off with a knife-edge scraper, and measurements were performed for water displacement, elongation and thermal conductivity. The samples were then reinserted into the pressure seals and reimmersed into the appropriate test fluid. In the third group of tests, tests were performed with a single oil-water mixture with the test temperature decreasing from +10°C to -4°C, again at 2°C intervals. For some of the oil-water mixtures, the suit-material samples could not be removed from the test fluids at -4°C and -2°C due to ice formation near the bottom of the test containers; hence no measurements could be performed for these cases.

The results for this test series are shown tabulated in Tables 3.1 to 3.11. The variations in the values of k are also shown plotted in Figs. 8.1 to 8.11. Several interesting features are apparent from the tables and figures. In general, the variations in the thicknesses of the suit-material samples are small. The difficulties associated with the measurement of sample thickness have already been noted. Therefore, only the values of the sample thicknesses at the end of each run are shown in Tables 3.1 to 3.11. For the same reason, any changes in thickness are <u>not</u> included in the calculation of the changes in volume or in any other calculations shown in the tables.

From the tables it can be seen that the samples undergo an elongation of less than 1% for the SAE 40 oil-water mixture and of almost 5% for the #2 Fuel oil-water mixture. In the previous test series (22 hours of continuous immersion in the test oils at 0°C), no noticeable elongation was observed. Thus, the foregoing results suggest

TABLE 3.1 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 1 Test Fluid: LaRossa Crude + fresh water										
Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.280
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{7}{32}$	$4\frac{7}{32}$	$4\frac{1}{4}$
Water displacement, (net) D cc		160	185	175	180	200	190	200	200	210
Temperature, ^{o}F Foam 	T_1	122.3	110.5	113.4	122.9	113.5	102.8	100.4	108.0	107.7
		122.8	110.7	114.1	123.6	113.8	102.9	100.7	108.6	108.3
	T_2	114.4	104.0	104.3	114.7	106.5	95.9	93.5	101.4	99.3
		114.9	104.3	105.1	115.4	106.8	96.1	93.8	102.0	100.1
	T_3	92.4	84.4	82.1	94.5	89.6	78.3	76.4	86.1	80.8
		92.8	85.0	83.0	95.1	90.0	78.4	76.8	86.8	81.5
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.008	0.015	0.015	0.023	0.031	0.031	0.038
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2\left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.015	0.031	0.031	0.046	0.062	0.062	0.078
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.156	0.094	0.125	0.250	0.188	0.250	0.250	0.313
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.156	0.079	0.094	0.219	0.142	0.188	0.188	0.235
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.029	0.028	0.033	0.032	0.035	0.034	0.034	0.034	0.036
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	-0.034	0.124	0.110	0.210	0.158	0.175	0.182	0.230
Insulation in CLO units		0.866	0.897	0.771	0.780	0.716	0.746	0.737	0.733	0.704

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

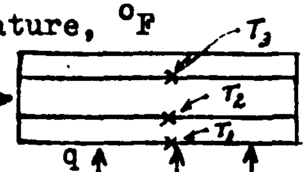
TABLE 3.2 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 2 Test Fluid: Murban Crude + fresh water

Test temperature ^oC		Virgin Sample	-4	-2	0^o	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.285
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{7}{64}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{3}{16}$	$4\frac{7}{32}$
Water displacement, (net) D cc		160	185	185	180	175	185	195	190	200
Temperature, ^oF Foam → 	T_1	116.6	109.1	112.1	121.1	110.4	99.7	97.8	110.4	109.1
		117.2	109.2	112.3	121.3	110.9	99.8	98.2	110.5	109.8
	T_2	109.6	102.9	105.3	112.4	103.6	92.7	91.2	103.8	101.9
		110.4	103.0	105.4	112.6	103.9	93.0	91.6	103.9	102.6
	T_3	90.5	84.9	85.0	89.1	87.4	75.4	74.0	86.1	85.2
		91.1	85.2	85.3	89.3	87.5	75.6	74.3	86.3	85.7
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.00	0.00	0.004	0.008	0.008	0.023	0.031
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2\left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.00	0.00	0.008	0.015	0.015	0.046	0.062
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.156	0.156	0.125	0.094	0.156	0.219	0.188	0.250
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.156	0.156	0.125	0.086	0.141	0.204	0.142	0.188
Thermal Conduct. k, Btu/hr-ft-^oF *		0.029	0.030	0.029	0.032	0.035	0.035	0.032	0.033	0.034
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.059	0.028	0.129	0.227	0.206	0.105	0.143	0.171
Insulation in CLO units		0.881	0.832	0.857	0.780	0.718	0.730	0.797	0.771	0.752

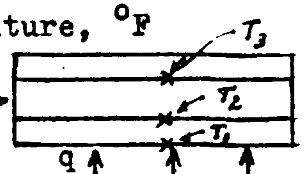
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.3 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 3 Test Fluid: SAE 40 + fresh water										
Test temperature ^oC		Virgin Sample	-4	-2	0^o	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.275
Diameter of inscribed circle, d inches		$4\frac{3}{32}$			$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{7}{64}$	$4\frac{7}{64}$	$4\frac{7}{64}$
Water displacement, (net) D cc		160			190	195	185	185	200	210
Temperature, ^oF Foam → 	T_1	123.4			116.9	112.6	96.8	97.5	114.0	110.8
		123.8			117.9	112.7	97.7	98.0	114.5	111.4
	T_2	116.1			108.1	104.2	88.8	90.3	107.0	101.8
		116.1			109.2	104.7	89.8	91.0	107.4	102.7
	T_3	93.2			85.2	84.8	71.4	73.3	90.5	82.0
		93.5			86.4	85.4	72.3	73.8	90.7	82.7
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-			0.00	0.00	0.00	0.004	0.004	0.004
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-			0.00	0.00	0.00	0.008	0.008	0.008
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-			0.188	0.219	0.156	0.156	0.250	0.313
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-			0.188	0.219	0.156	0.148	0.242	0.305
Thermal Conduct. k, Btu/hr-ft-^oF *		0.028			0.029	0.036	0.035	0.033	0.035	0.036
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-			0.062	0.313	0.262	0.207	0.273	0.295
Insulation in CLO units		0.916			0.863	0.698	0.726	0.759	0.720	0.708

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.4 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST #4 Test Fluid: #2 Fuel oil + fresh water										
Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265			-	-	-	-	-	0.260
Diameter of inscribed circle, d inches		$4\frac{3}{32}$			$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{7}{32}$	$4\frac{1}{4}$	$4\frac{1}{4}$
Water displacement, (net) D cc		210			280	285	275	295	305	305
Temperature, ^{o}F  Foam	T_1	124.5			123.6	116.5	99.9	96.6	111.2	111.5
		125.3			124.1	117.0	100.2	97.2	111.7	112.1
	T_2	116.8			115.5	109.7	92.3	88.7	102.9	102.3
		117.6			116.0	110.4	92.5	89.4	103.5	103.0
	T_3	87.4			81.8	82.5	66.1	67.4	91.8	78.7
		88.0			82.4	82.6	67.4	68.6	82.3	79.1
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-			0.015	0.023	0.023	0.031	0.038	0.038
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-			0.031	0.046	0.046	0.062	0.078	0.078
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-			0.333	0.357	0.310	0.405	0.452	0.452
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-			0.302	0.311	0.264	0.343	0.374	0.374
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.052			0.046	0.045	0.059	0.070	0.073	0.073
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-			-0.115	-0.138	0.136	0.333	0.386	0.394
Insulation in CLO units		0.482			0.544	0.559	0.424	0.362	0.348	0.346

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

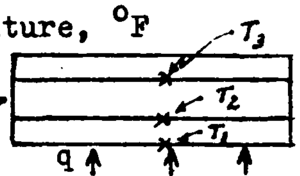
TABLE 3.5 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 5 Test Fluid: #6 Fuel Oil + fresh water

Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.285
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{3}{16}$
Water displacement, (net) D cc		150	170	165	170	165	180	180	180	190
Temperature, ^{o}F	T_1	120.3	112.0	112.6	116.1	114.4	102.6	94.6	111.2	109.4
		121.2	112.3	112.9	116.6	115.0	103.0	95.2	112.1	109.8
Foam	T_2	112.3	105.0	105.4	108.6	106.8	94.8	87.4	103.7	101.1
		113.3	105.2	105.7	109.0	107.4	95.3	88.1	104.7	101.7
	T_3	89.9	85.4	85.8	89.4	86.5	75.4	71.5	87.5	82.0
		86.6	85.5	85.9	89.5	86.6	75.8	72.3	88.5	82.5
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.008	0.015	0.015	0.023	0.023	0.023	0.023
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2\left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.015	0.031	0.031	0.046	0.046	0.046	0.046
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.133	0.100	0.133	0.100	0.200	0.200	0.200	0.267
Density Change $\frac{\Delta\rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.133	0.085	0.102	0.069	0.154	0.154	0.154	0.221
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.027	0.031	0.031	0.032	0.031	0.033	0.036	0.036	0.035
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.125	0.147	0.173	0.132	0.213	0.313	0.309	0.301
Insulation in CLO units		0.926	0.824	0.808	0.790	0.818	0.764	0.706	0.708	0.712

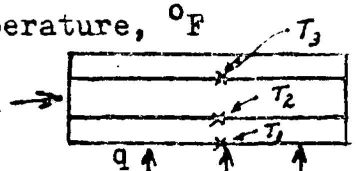
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.6 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 6 Test Fluid: LaRossa Crude + 35‰ salt water										
Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.270
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{7}{32}$	$4\frac{7}{32}$
Water displacement, (net) D cc		175	200	185	220	215	210	215	220	220
Temperature, ^{o}F Foam → 	T_1	115.2	115.4	121.7	106.9	110.8	112.1	107.1	113.5	115.0
		116.0	115.9	122.0	107.8	110.9	112.4	107.4	114.5	115.1
	T_2	106.0	106.6	113.6	98.3	103.1	104.5	99.6	105.7	106.3
		107.0	107.2	114.0	99.3	103.3	104.7	100.2	106.7	106.7
	T_3	81.8	84.5	90.3	79.4	83.6	84.9	81.1	87.9	84.9
		82.7	85.6	91.0	80.4	84.5	85.3	81.7	88.6	85.1
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.008	0.015	0.015	0.015	0.015	0.023	0.031	0.031
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.015	0.031	0.031	0.031	0.031	0.043	0.062	0.062
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.143	0.057	0.257	0.229	0.200	0.229	0.257	0.257
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.128	0.026	0.226	0.198	0.169	0.186	0.195	0.195
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.030	0.033	0.029	0.032	0.035	0.034	0.033	0.033	0.034
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.115	-0.007	0.088	0.180	0.136	0.108	0.112	0.159
Insulation in CLO units		0.854	0.766	0.860	0.785	0.724	0.752	0.771	0.768	0.737

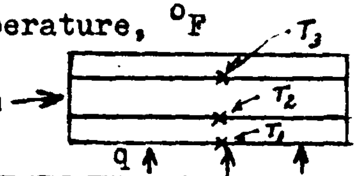
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.7 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST #7	Test Fluid: Murban Crude + 35‰ salt water									
Test temperature °C		Virgin Sample	-4	-2	0°	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.270
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{3}{16}$
Water displacement, (net) D cc		165	190	180	200	200	205	195	210	210
Temperature, °F 	T_1	117.4	114.5	1,9.1	112.1	114.7	112.0	98.3	112.8	112.2
		118.6	114.7	119.8	112.6	115.3	112.4	99.0	113.8	112.6
	T_2	108.7	107.6	110.2	103.3	106.3	103.1	92.1	104.7	103.2
		108.0	107.9	111.0	104.2	107.2	103.7	92.7	105.8	103.7
	T_3	80.0	87.3	87.9	81.4	86.2	81.0	76.6	86.1	82.0
		80.9	87.5	88.4	82.4	86.9	81.9	76.8	87.0	82.3
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.008	0.015	0.015	0.015	0.023	0.023	0.023
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.015	0.031	0.031	0.031	0.046	0.046	0.046
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.152	0.091	0.212	0.212	0.242	0.182	0.273	0.273
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.152	0.076	0.181	0.181	0.181	0.138	0.227	0.227
Thermal Conduct. k, Btu/hr-ft-°F *		0.030	0.029	0.032	0.032	0.034	0.034	0.031	0.032	0.035
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	-0.023	0.054	0.084	0.130	0.114	0.040	0.077	0.177
Insulation in CLO units		0.843	0.863	0.800	0.778	0.746	0.757	0.810	0.783	0.716

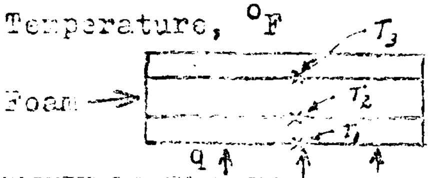
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.8 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 8	Test Fluid: SAE 40 + 35% salt water									
Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.260
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{1}{8}$
Water displacement, (net) D cc		160	185	185	200	195	200	195	205	200
Temperature, ^{o}F 	T_1	118.9	114.5	119.1	116.6	120.4	116.6	98.9	117.7	112.0
		120.1	115.2	119.7	117.1	120.6	116.8	99.8	118.6	112.7
	T_2	108.0	106.4	109.5	106.4	111.4	107.7	90.6	109.0	101.7
		109.2	107.1	110.3	107.4	111.7	107.8	91.8	109.9	102.8
	T_3	80.6	86.9	87.3	83.7	90.2	86.2	73.5	89.7	80.5
		81.4	87.5	87.9	84.6	90.3	86.3	74.6	90.3	81.3
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.00	0.008	0.008	0.008	0.008	0.008	0.008
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.00	0.015	0.015	0.015	0.015	0.015	0.015
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.156	0.156	0.250	0.219	0.250	0.219	0.281	0.250
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.156	0.156	0.235	0.235	0.235	0.204	0.266	0.235
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.031	0.033	0.035	0.035	0.035	0.036	0.036	0.035	0.038
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.082	0.131	0.157	0.154	0.180	0.170	0.141	0.229
Insulation in CLO units		0.824	0.761	0.218	0.712	0.714	0.698	0.704	0.722	0.670

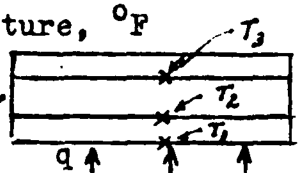
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.9 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 9	Test Fluid: #2 Fuel Oil + 35‰ salt water									
Test temperature ^{o}C		Virgin Sample	-4	-2	0^{o}	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265			-	-	-	-	-	0.265
Diameter of inscribed circle, d inches		$4\frac{3}{32}$			$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{7}{32}$	$4\frac{9}{32}$	$4\frac{5}{16}$	$4\frac{5}{16}$
Water displacement, (net) D cc		165			225	230	225	230	240	240
Temperature, ^{o}F 	T_1	119.3			111.4	117.2	114.4	100.5	117.4	111.1
		120.1			111.8	117.7	114.8	100.0	118.1	111.9
	T_2	109.1			102.1	108.6	105.7	92.0	110.6	101.[illegible]
		110.2			103.0	109.3	106.3	92.9	111.4	102.5
	T_3	81.6			80.6	86.2	83.4	73.0	83.5	78.6
		83.0			81.4	86.9	84.0	75.9	84.4	79.6
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-			0.015	0.015	0.031	0.046	0.053	0.053
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-			0.031	0.031	0.062	0.094	0.110	0.110
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-			0.364	0.394	0.364	0.394	0.455	0.455
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-			0.333	0.363	0.302	0.300	0.345	0.345
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.029			0.034	0.030	0.032	0.035	0.032	0.033
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-			0.179	0.038	0.103	0.207	0.093	0.138
Insulation in CLO units		0.869			0.737	0.837	0.788	0.720	0.795	0.764

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.10 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 10 Test Fluid: #6 Fuel Oil + 35‰ salt water										
Test temperature ^oC		Virgin Sample	-4	-2	0^o	+2	+4	+6	+8	+10
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.290
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{3}{16}$
Water displacement, (net) D cc		175	205	195	200	215	210	210	225	225
Temperature, ^oF  Foam	T_1	117.5	111.4	113.2	111.6	113.2	116.4	99.9	112.4	110.2
		118.5	112.1	113.7	112.3	114.1	117.2	100.5	113.1	111.2
	T_2	107.7	102.7	103.5	103.3	103.5	107.1	92.2	103.6	99.2
		108.9	103.6	104.4	103.9	104.7	108.0	92.9	104.5	100.7
	T_3	82.1	82.6	81.2	82.6	83.3	86.7	75.7	85.2	77.5
		83.0	83.8	82.6	83.3	84.3	87.7	76.3	86.1	79.0
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.008	0.008	0.015	0.015	0.015	0.023	0.023	0.023
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.015	0.015	0.031	0.031	0.031	0.046	0.046	0.046
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.171	0.114	0.143	0.229	0.200	0.200	0.286	0.286
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.156	0.099	0.112	0.198	0.169	0.154	0.240	0.240
Thermal Conduct. k, Btu/hr-ft-^oF *		0.029	0.034	0.035	0.033	0.036	0.036	0.037	0.038	0.038
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.176	0.207	0.128	0.255	0.241	0.276	0.293	0.307
Insulation in CLO units		0.869	0.739	0.720	0.771	0.692	0.700	0.681	0.672	0.665

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

TABLE 3.11 RESULTS OF VARIABLE-TEMPERATURE TESTS

TEST # 11	Test Fluid: #6 Fuel Oil + 35‰ salt water									
Test temperature ^{o}C		Virgin Sample	+10	+8	+6	+4	+2	0^{o}	-2	-4
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.280
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{9}{64}$	$4\frac{9}{64}$	$4\frac{5}{32}$	$4\frac{5}{32}$
Water displacement, (net) D cc		175	200	195	210	210	210	215	220	220
Temperature, ^{o}F	T_1	120.9	114.3	118.7	111.7	115.6	110.7	111.2	111.6	118.5
		121.8	115.5	119.3	112.7	116.8	111.4	112.5	112.6	119.0
Foam	T_2	112.5	106.2	110.7	103.7	107.1	102.1	103.6	103.0	109.8
		113.5	107.7	111.5	104.9	108.4	103.0	104.9	104.1	110.4
	T_3	88.2	87.8	90.1	85.7	86.6	79.9	86.2	82.5	85.6
		88.9	89.3	91.2	86.8	88.2	81.3	87.3	84.4	86.5
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.008	0.008	0.008	0.011	0.011	0.015	0.015
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2\left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.015	0.015	0.015	0.023	0.023	0.031	0.031
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.143	0.114	0.200	0.200	0.200	0.229	0.257	0.257
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.143	0.099	0.185	0.185	0.177	0.206	0.226	0.226
Thermal Conduct. k, Btu/hr-ft-^{o}F *		0.026	0.031	0.031	0.033	0.030	0.031	0.031	0.032	0.030
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.167	0.167	0.236	0.122	0.164	0.167	0.228	0.125
Insulation in CLO units		0.958	0.821	0.821	0.775	0.854	0.824	0.821	0.780	0.851

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.
*All values shown in row have been rounded-off to three decimal places.

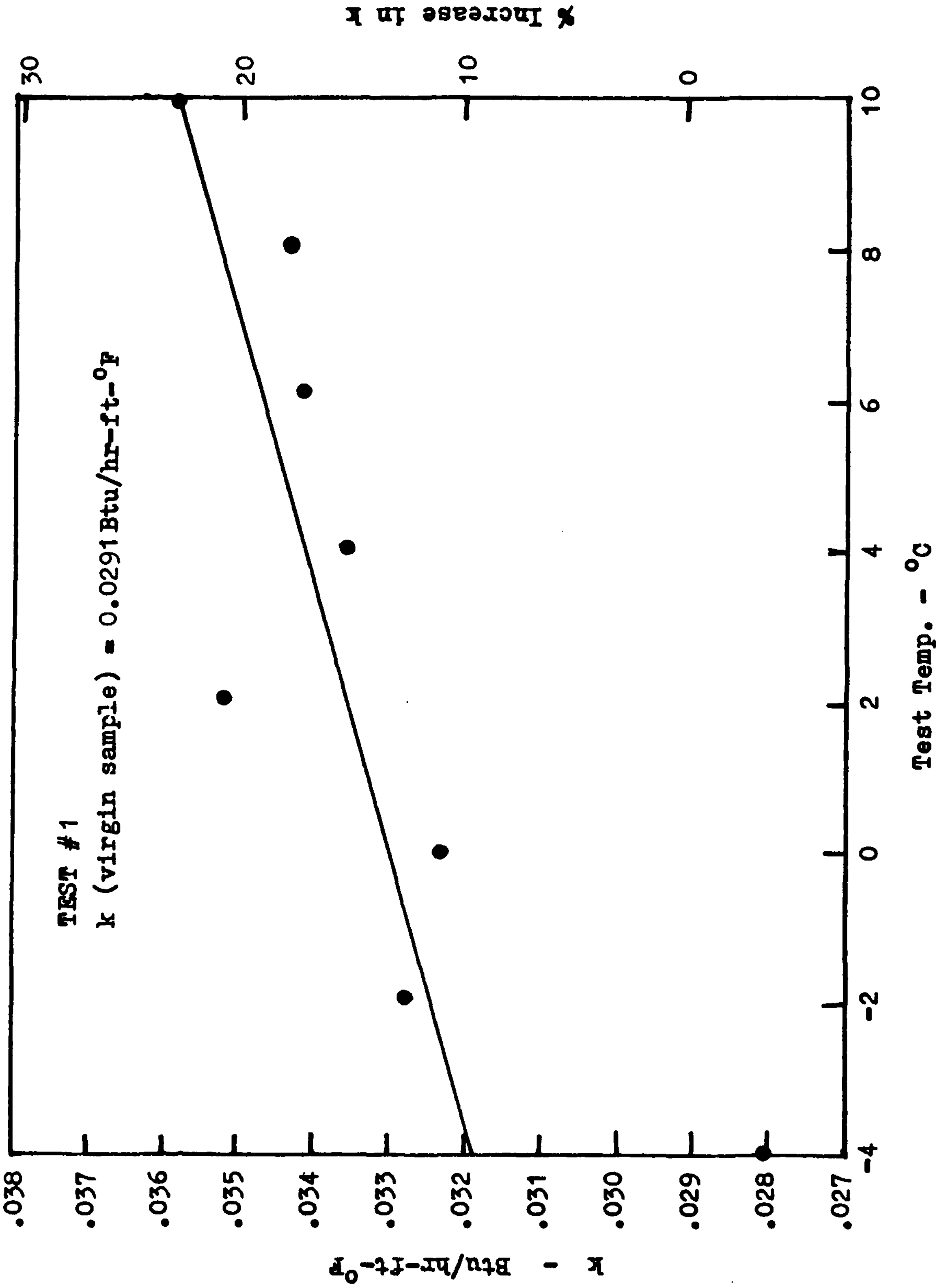


FIGURE 8.1 - k VERSUS TEST TEMPERATURE

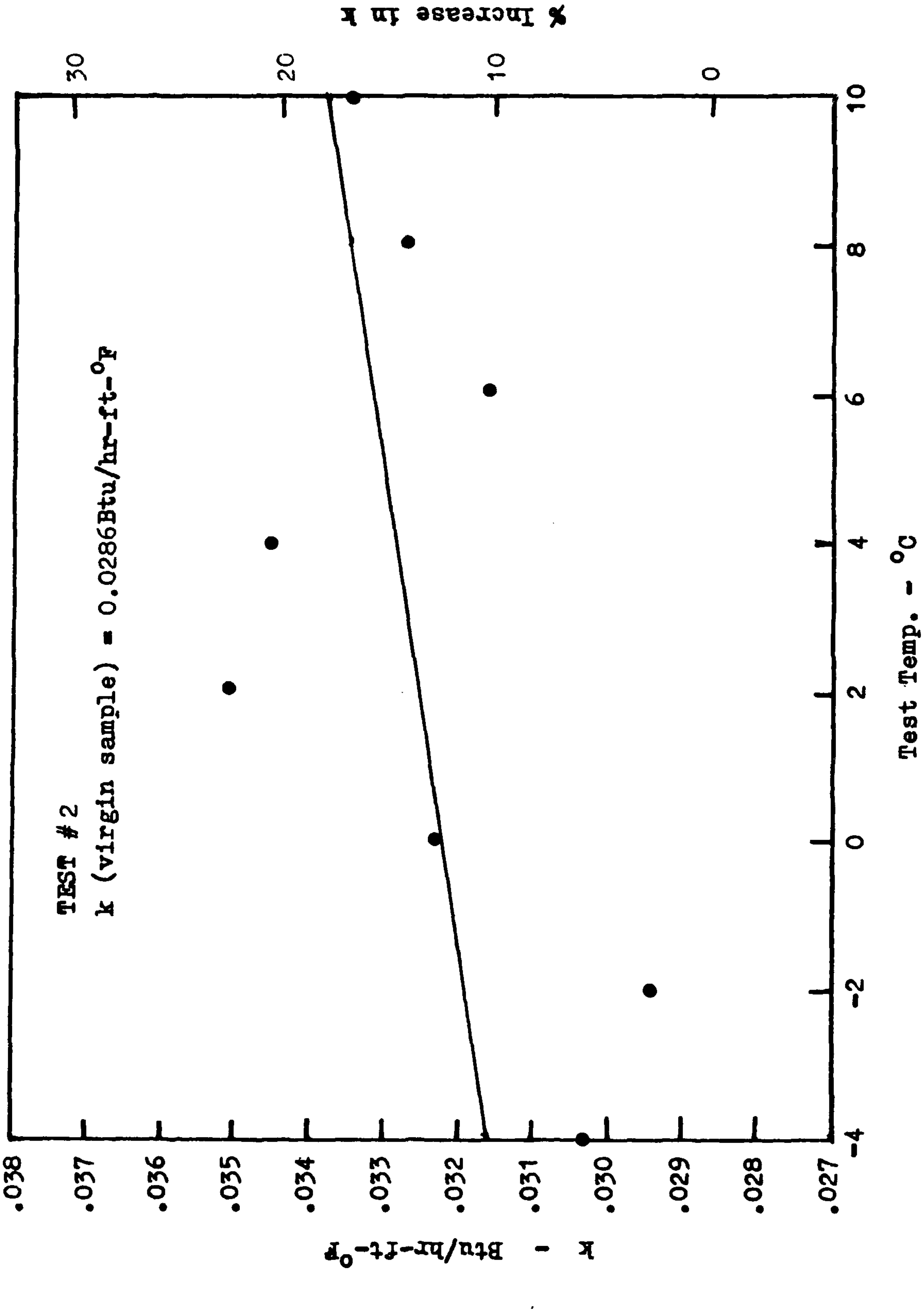


FIGURE 8.2 - k VERSUS TEST TEMPERATURE

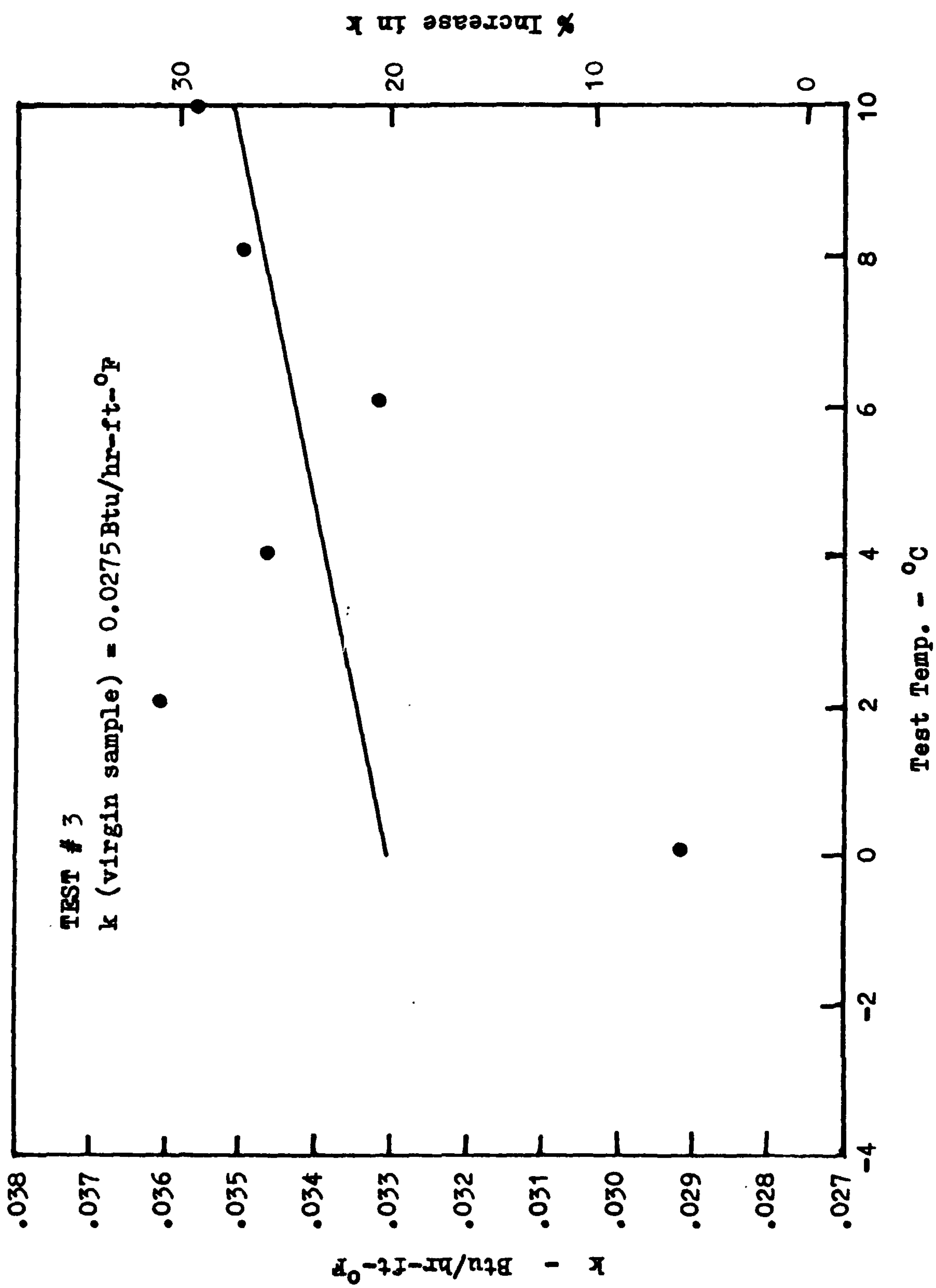


FIGURE 8.3 - k VERSUS TEST TEMPERATURE

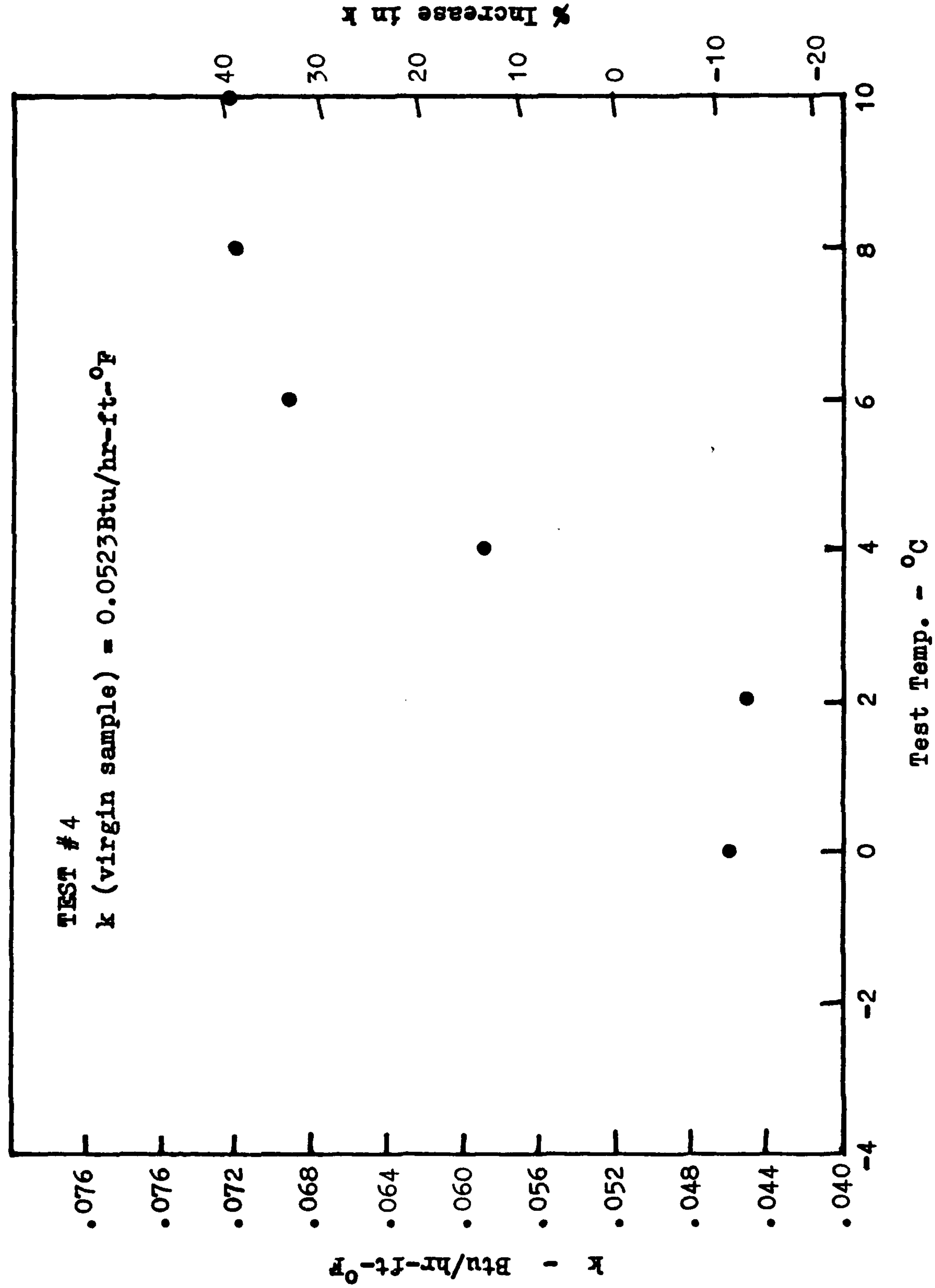


FIGURE 8.4 - k VERSUS TEST TEMPERATURE

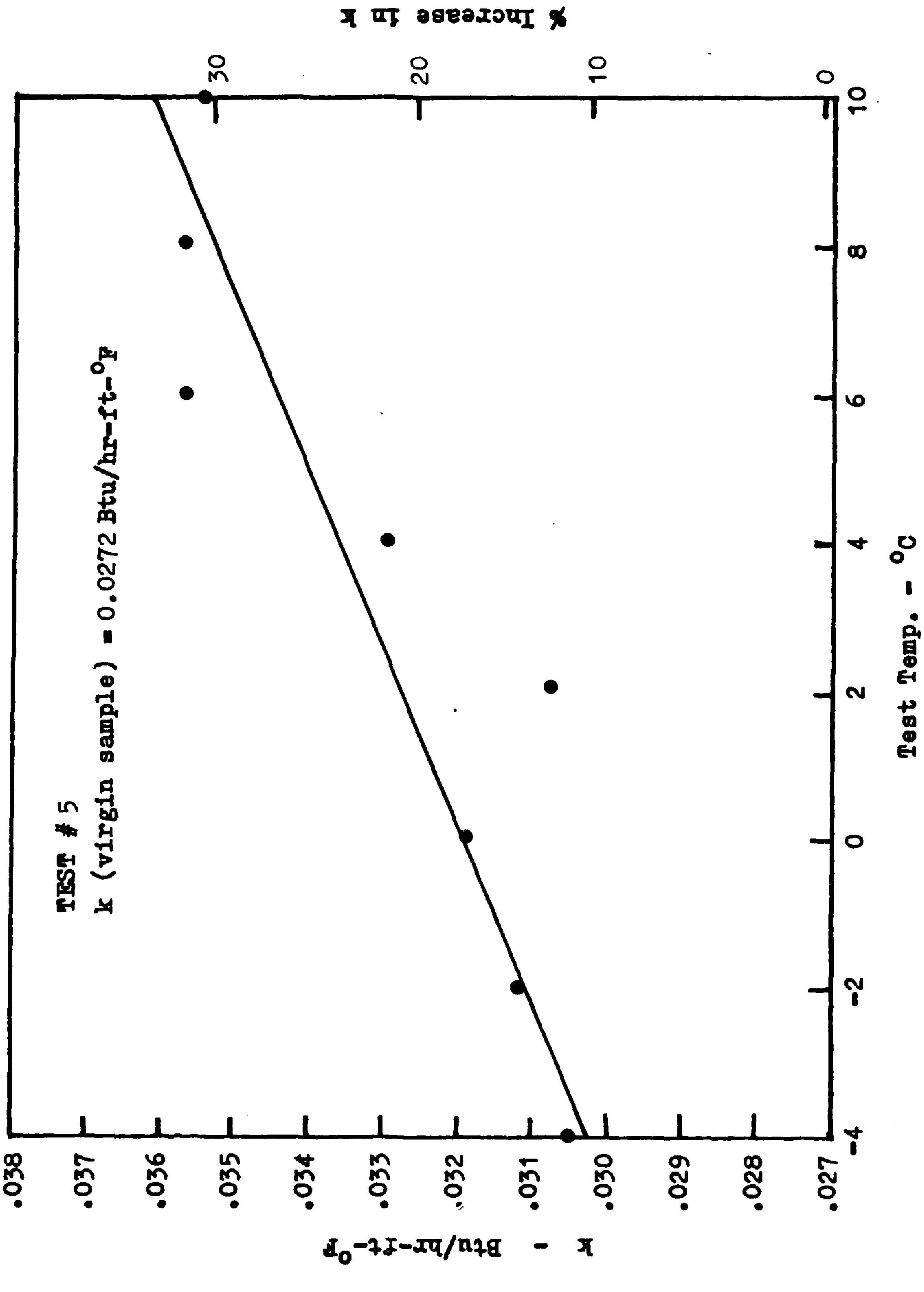


FIGURE 8.5 - k VERSUS TEST TEMPERATURE

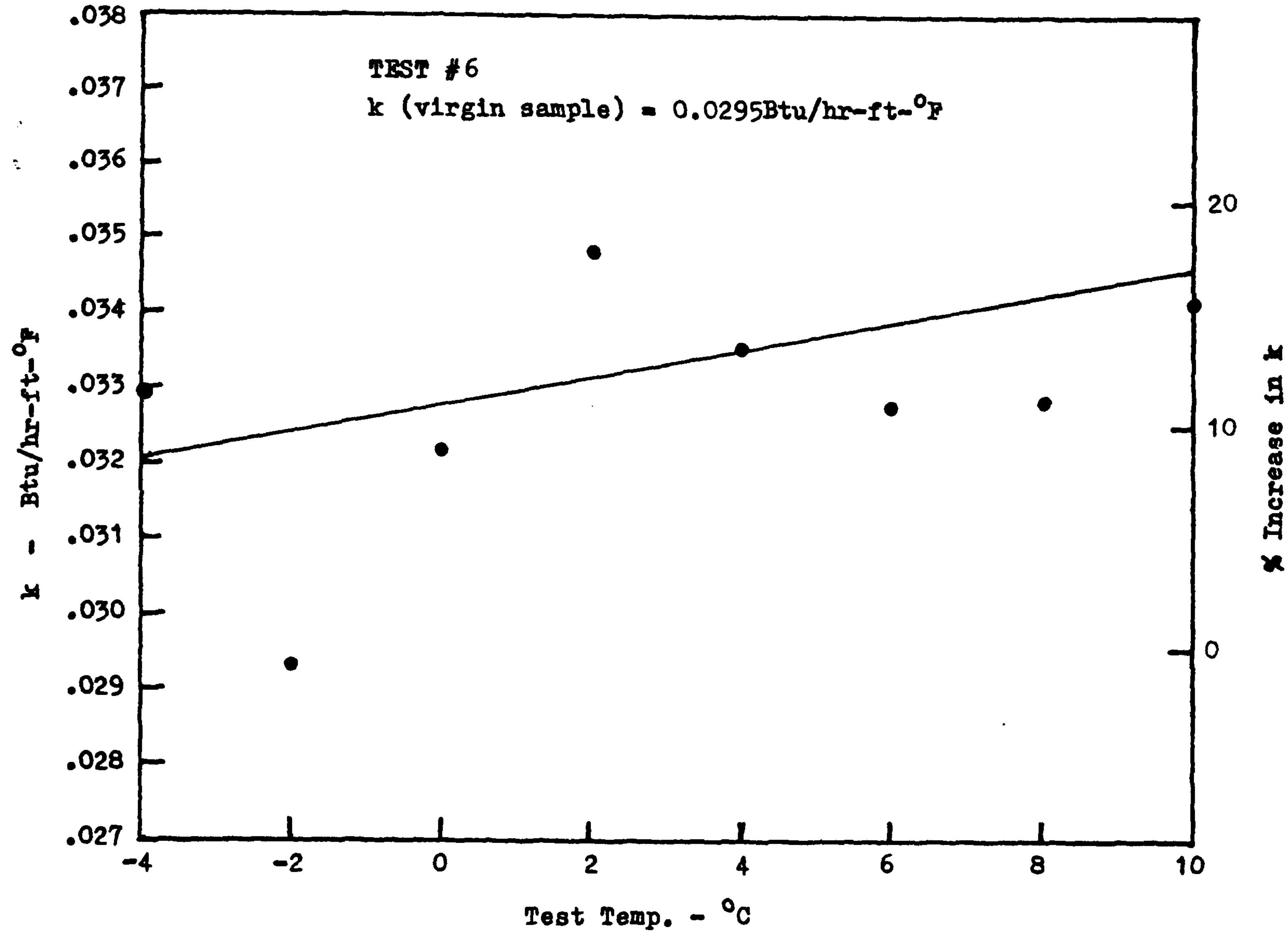


FIGURE 8.6 - k VERSUS TEST TEMPERATURE

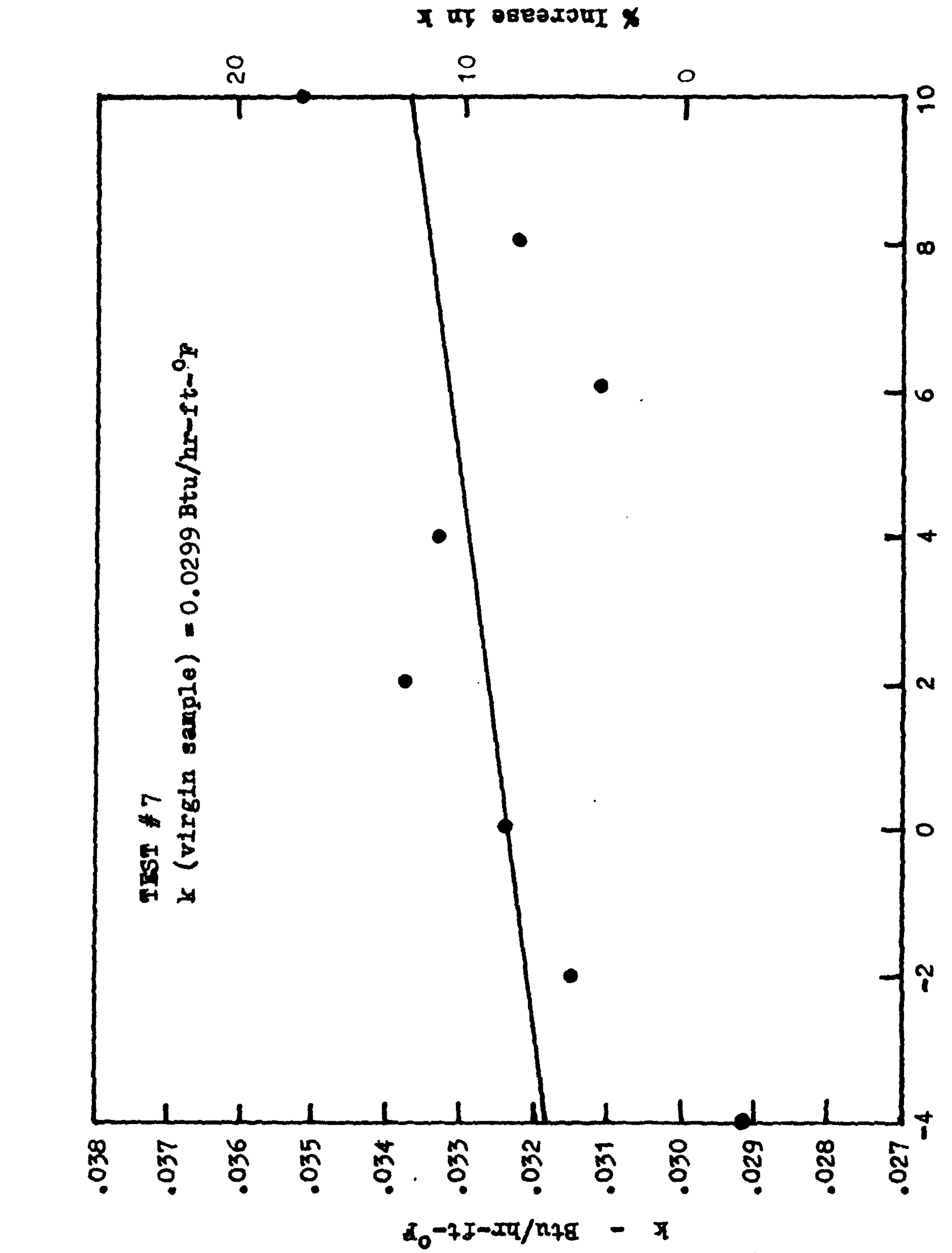


FIGURE 8.7 - k VERSUS TEST TEMPERATURE

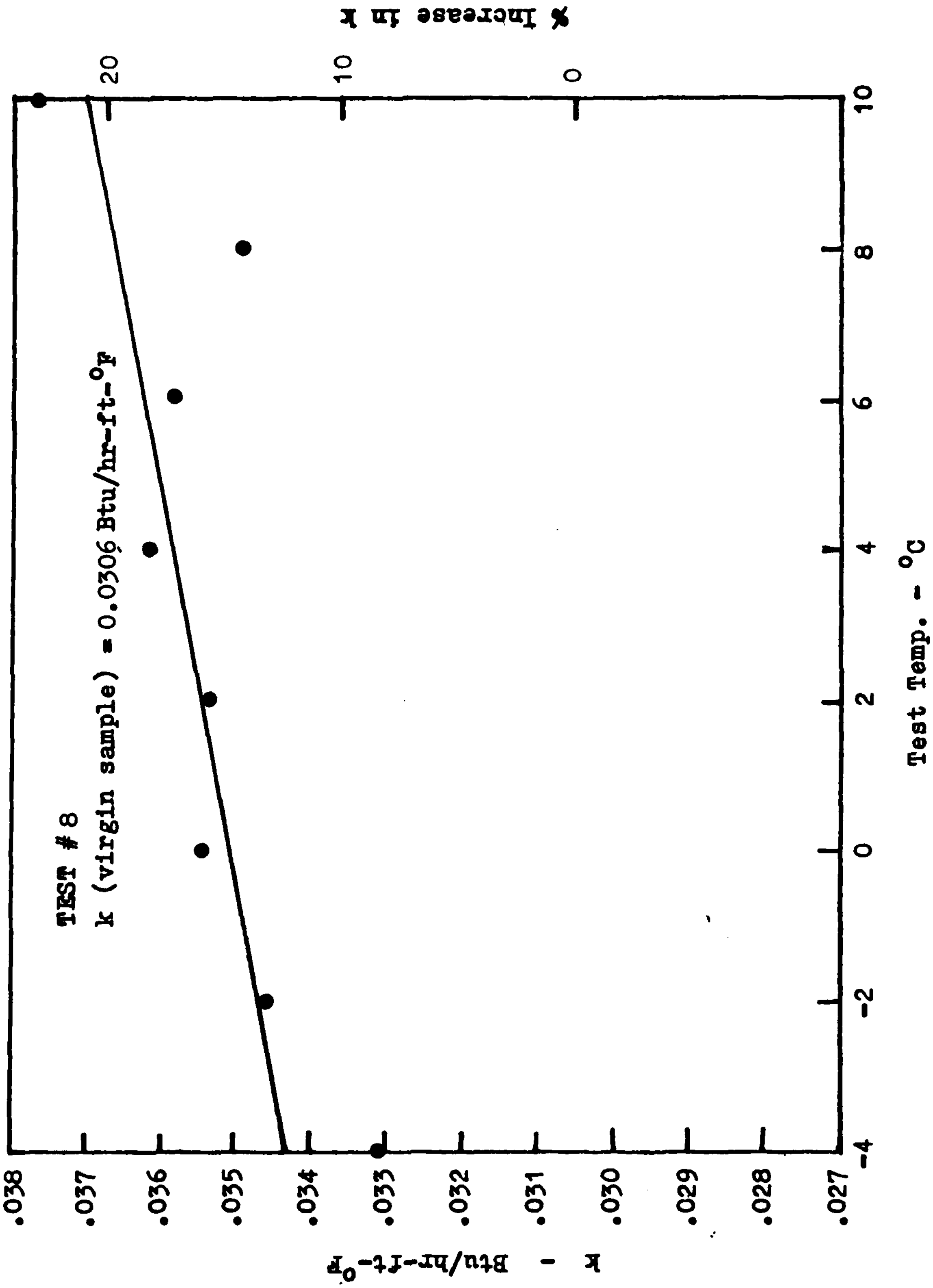


FIGURE 8.8 - k VERSUS TEST TEMPERATURE

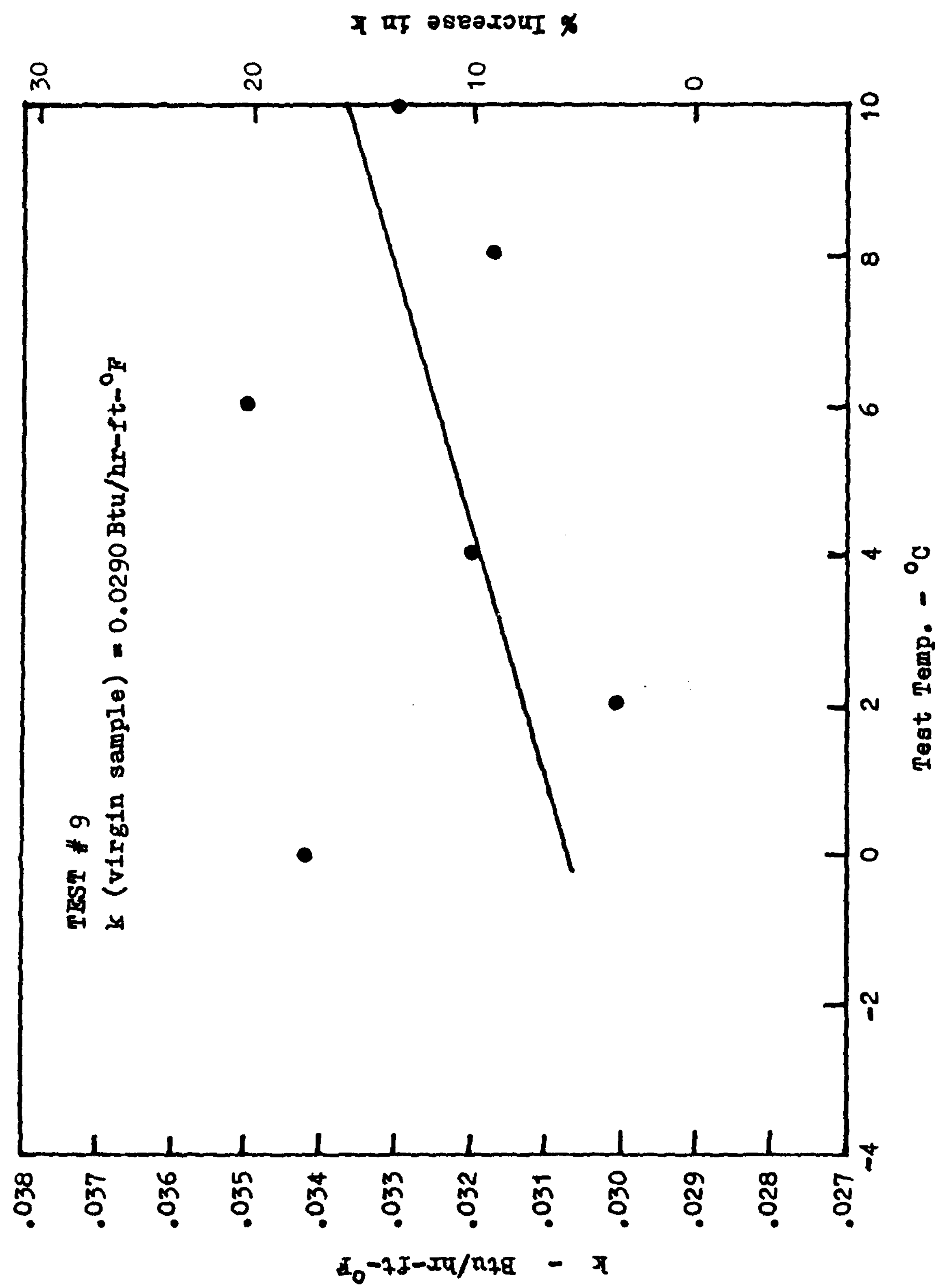


FIGURE 8.9 - k VERSUS TEST TEMPERATURE

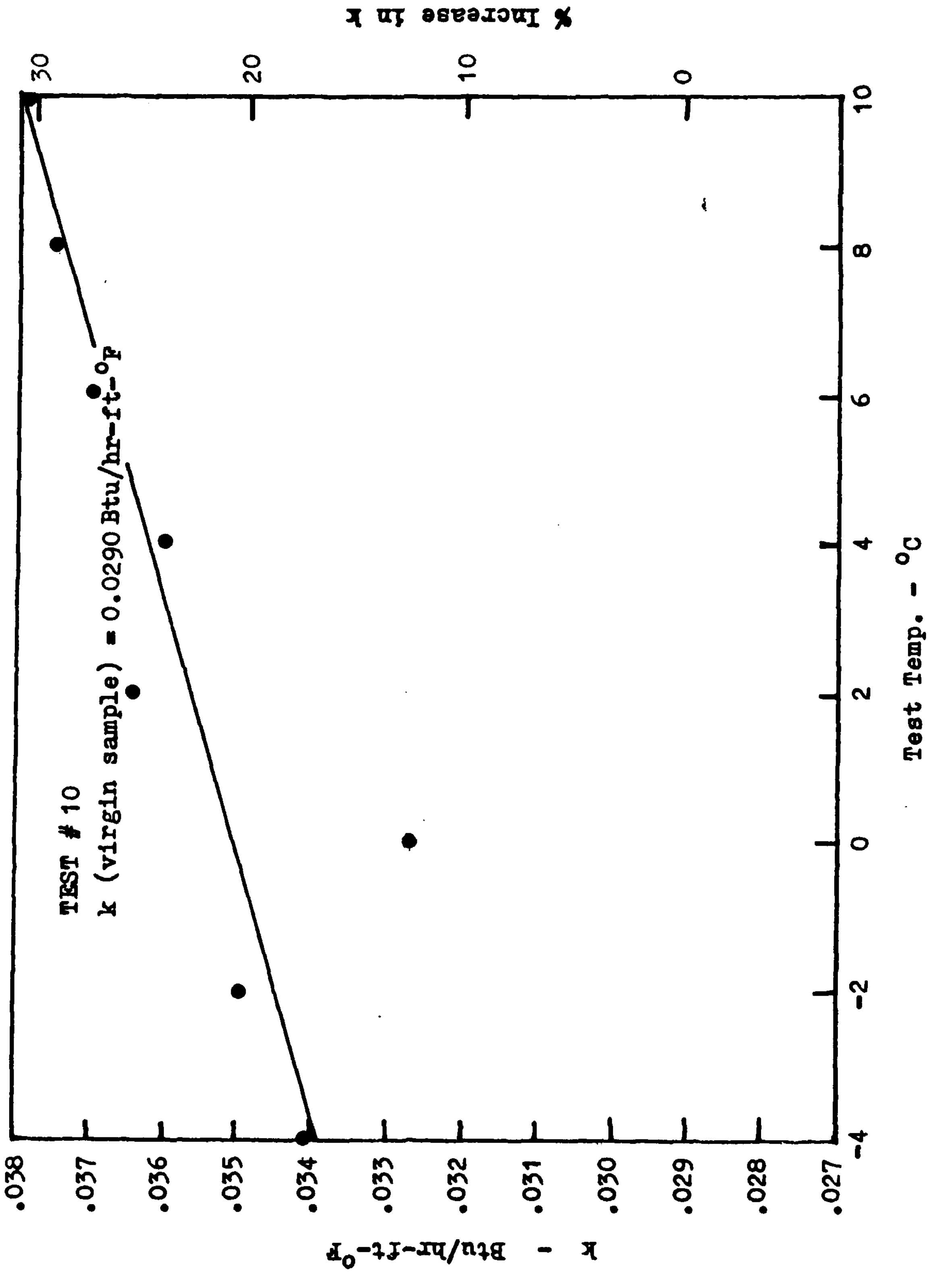


FIGURE 8.10 - k VERSUS TEST TEMPERATURE

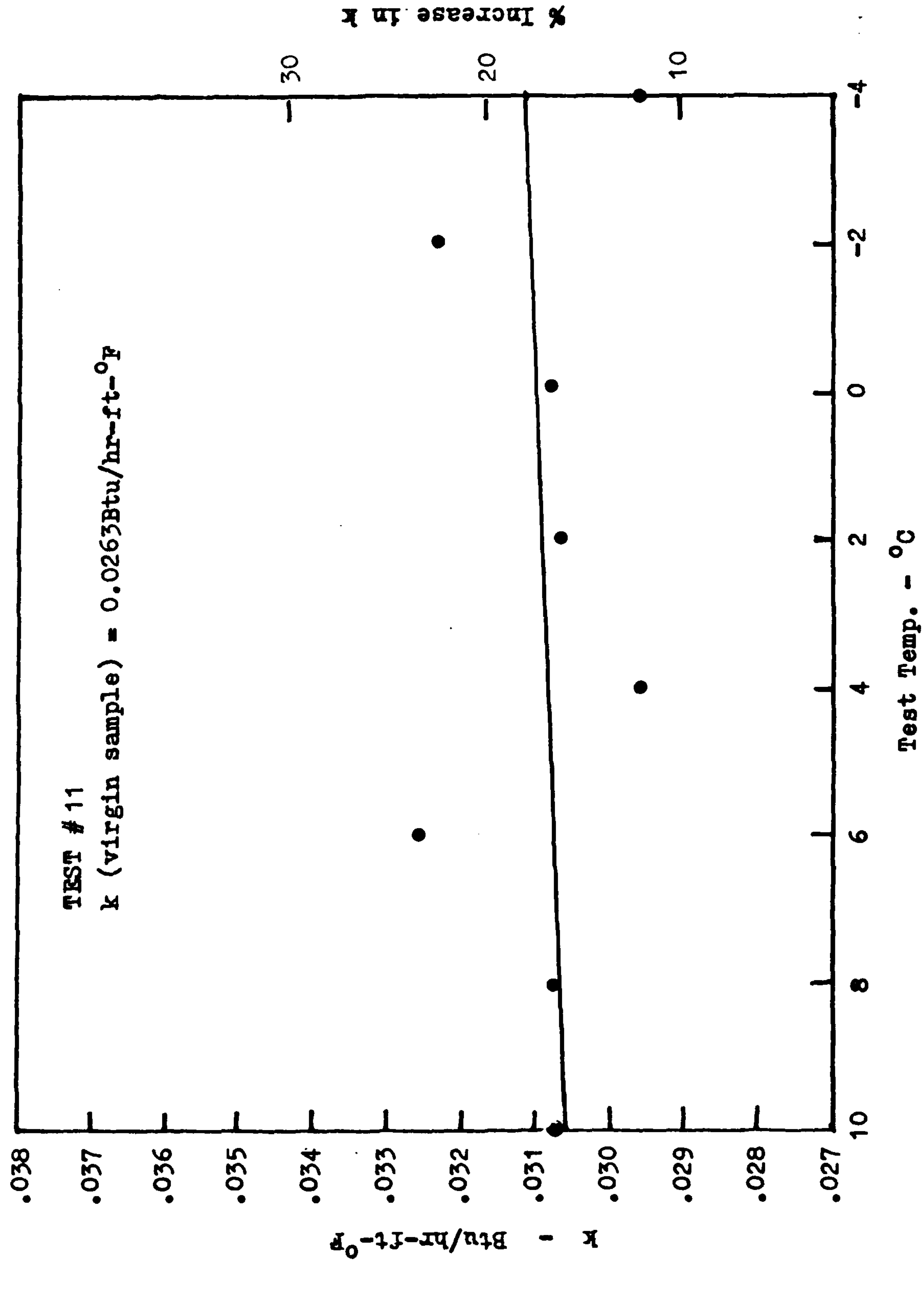


FIGURE 8.11 - k VERSUS TEST TEMPERATURE

that the observed elongations may be an effect of subjecting the samples to varying test temperatures of from -4° to $+10^{\circ}C$. Also contributing to the elongation of the samples may be the repeated (8 times in all) cycles of immersion into, and removal out of, the test fluids, and the scraping of the superficial fluid from their surfaces.

The observed increase in the sample density due to test-fluid absorption ranges from 10% to over 35%, the largest being for the #2 Fuel-oil case. Note that the largest increase in the sample density in the previous test series was for the #2 Fuel-oil case also and was about 35%. As noted earlier, all the oil-water emulsions appeared to be much more viscous than the parent oils themselves. Since the superficial test fluids from the sample surfaces were removed by gentle scraping and since the degree of which the absorbed oil is expressed out of the foam by scraping may vary from case to case, the "observed" mass and density changes should be viewed with caution.

The thermal conductivity values at various test temperatures are shown in Figures 8.1 to 8.11. The results for the tests with increasing test-fluid temperatures indicate that k generally increased as the tests progressed and as the samples experienced an increase in the test temperature from -4° to $+10^{\circ}C$. The percentage increase in k seems to range from $\sim$10% for the initial tests at $-4^{\circ}C$ to from 20 to 30% at the completion of the tests at $+10^{\circ}C$, except for the #6 Fuel oil-water case wherein it is about 40%. Since the difference between the increases in the value of k for the #6 Fuel oil mix with fresh water and salt water is not very significant and since the 35%. salt water mix is likely to be more representative of the seawater mix, the #6 Fuel oil-salt water emulsion case was taken as the "worst case" scenario, and the last series of tests with decreasing test temperatures (from $+10^{\circ}C$ to $-4^{\circ}C$) was performed for this case.

The percentage increase in k for the "worst case" of #6 Fuel oil-salt water emulsion with decreasing test temperatures is only $\sim$20%, which is much smaller than the 20 to 40% increase for the case of increasing test temperatures.

Test 4 was carried out using a sample with a zipper and an end closure of the zipper. When the sample was removed from the pressure seals, the test fluid was found on the inner surface of the sample. It is not clear whether the fluid penetrated to the inside through the zipper itself or only through the end closure section of the zipper. The zipper section also had an additional foam flap on the inside so that the thickness of the sample at the location of the zipper was much higher than that of the remaining portion of the sample. The foregoing feature resulted in an air pocket existing between the sample and the upper acrylic plate of the TCM Box, when the sample was placed between the two plates. The thermocouples used in measuring the temperatures T_2 and T_3 were right below and right above the thicker section of the foam. Because of the aforementioned features, the observed value of k itself, as well as the observed values of the changes in k, for the case of the foam with a zipper have to be interpreted with caution.

Tests #5 and #6 were carried out with suit-material samples having a seam at the center. A comparison of the general trend of these results with those of their counterparts (Tests #10 and #1) indicates that the presence of a seam does not have a significant effect on the changes in k.

Cleaning Tests

The purpose of these tests was to examine the effects of cleaning the suit-material sample on its properties, after the sample has been kept immersed in the 'worst' test fluid at $0^{\circ}C$ for a period of at least 5 hours. The 'worst' test fluid, as was determined from the results of the variable-temperature tests, consisted of a mixture of #6 Fuel oil and 35‰ salt water in a 50:50 ratio by volume. In order to determine the optimum cleaning procedures, several preliminary cleaning tests were conducted with previously-used, suit-material samples. The results of cleaning were assessed by comparing the properties of the samples before and after cleaning. Tests in which the samples were soaked for about fifteen minutes in solutions (in lukewarm water) of a commercially available domestic dishwashing soap ("Joy") and a "heavy-duty" laundry detergent ("Wisk") showed that, while these cleaning agents removed some of the absorbed oil from the foam, they were not totally satisfactory. Somewhat better results were achieved when the foam was cleaned with an "industrial type" soap ("Lava"). Therefore, the last of the three aforementioned products was used in the actual tests.

In the tests themselves, the foam was first cleaned as noted above and then rinsed three times in lukewarm water ($\approx 100^{\circ}F$ in temperature). Any excess moisture was removed with paper toweling, and the foam was then dried by placing it on the warm lower acrylic plate of the TCM Box for about fifteen minutes. Finally, the thermal conductivity as well as the other properties of the foam were measured by using techniques already described. As noted in Table 4, all the measurements were performed twice, once soon after the sample was removed from the test fluid and once after it was cleaned and dried. In all, four complete cycles of immersion, cleaning and measurement were performed.

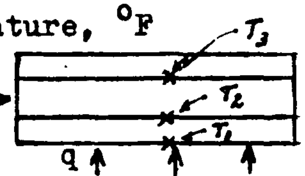
The results show that the sample undergoes a total elongation of $\approx 3\%$ by the end of four (4) test cycles; whereas, the observed increases in the sample density due to absorption of the test fluid and/or water ranges from ≈ 10 to 20%.

The thermal conductivities and the percent changes in k for each test cycle are shown in Fig. 9. The data show a general increase of from 20 to 30% in k for all the tests, indicating that 'the cleaning', per se, of the sample neither adversely affects the thermal conductivity, nor restores it to that of the virgin foam.

Stretch Tests

The purpose of this test series was to examine the effects of tensile loading (simulating the stretch associated with the wearing of the suit by the diver) on the properties of a suit-material sample when the sample is immersed in the 'worst' test fluid at $0^{\circ}C$ for a period of at least 5 hours. In the three test series described earlier, the samples were folded and pressure sealed in order to expose only their outer surfaces to the test fluids. To apply a uniform tensile loading across the foam cross section however, it is necessary that in the present test series the sample remain unfolded. To accomplish this, two 12" X 12" samples, with their inner surfaces facing each other, were cemented together (using neoprene cement) and, as an additional assurance of proper sealing, stitched (on a shoe-stitching machine) together at their four edges to form a single test sample. Of course, the application of the tensile loads as well as the measurement of the thermal conductivity will now have to take into account the fact that the test sample has double the thickness of the suit material.

TABLE 4 RESULTS OF CLEANING TESTS

Test temperature: 0°C Test Fluid: #6 Fuel Oil + 35‰ salt water										
Test cycle: a - before cleaning, b - after cleaning		Virgin Sample	Ia	Ib	IIa	IIb	IIIa	IIIb	IVa	IVb
Sample thickness, t inches		0.265	-	-	-	-	-	-	-	0.275
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{3}{32}$	$4\frac{1}{8}$	$4\frac{1}{8}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	$4\frac{7}{32}$	$4\frac{7}{32}$
Water displacement, (net) D cc		175	190	190	215	205	215	205	220	215
Temperature, °F  Foam	T_1	120.9	111.0	119.7	106.6	115.2	111.7	112.1	112.5	112.2
		121.7	112.0	120.1	107.8	115.4	111.9	112.4	113.3	112.7
	T_2	112.4	103.5	112.0	98.3	107.7	104.6	104.9	105.2	104.4
		113.1	104.6	112.5	99.6	108.0	104.9	105.4	106.0	105.2
	T_3	91.4	89.3	95.5	84.2	91.8	89.2	89.6	90.9	89.6
		92.0	90.2	96.2	85.4	92.1	89.6	90.2	91.7	90.6
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00	0.008	0.008	0.015	0.023	0.023	0.031	0.031
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.015	0.015	0.031	0.046	0.046	0.062	0.062
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.086	0.086	0.229	0.171	0.229	0.171	0.257	0.229
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.086	0.071	0.214	0.140	0.183	0.125	0.195	0.167
Thermal Conduct. k, Btu/hr-ft-°F X 10		0.324	0.386	0.387	0.421	0.400	0.391	0.386	0.395	0.415
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.191	0.194	0.299	0.234	0.207	0.191	0.219	0.281
Insulation in CLO units		0.778	0.653	0.651	0.599	0.630	0.645	0.653	0.638	0.607

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.

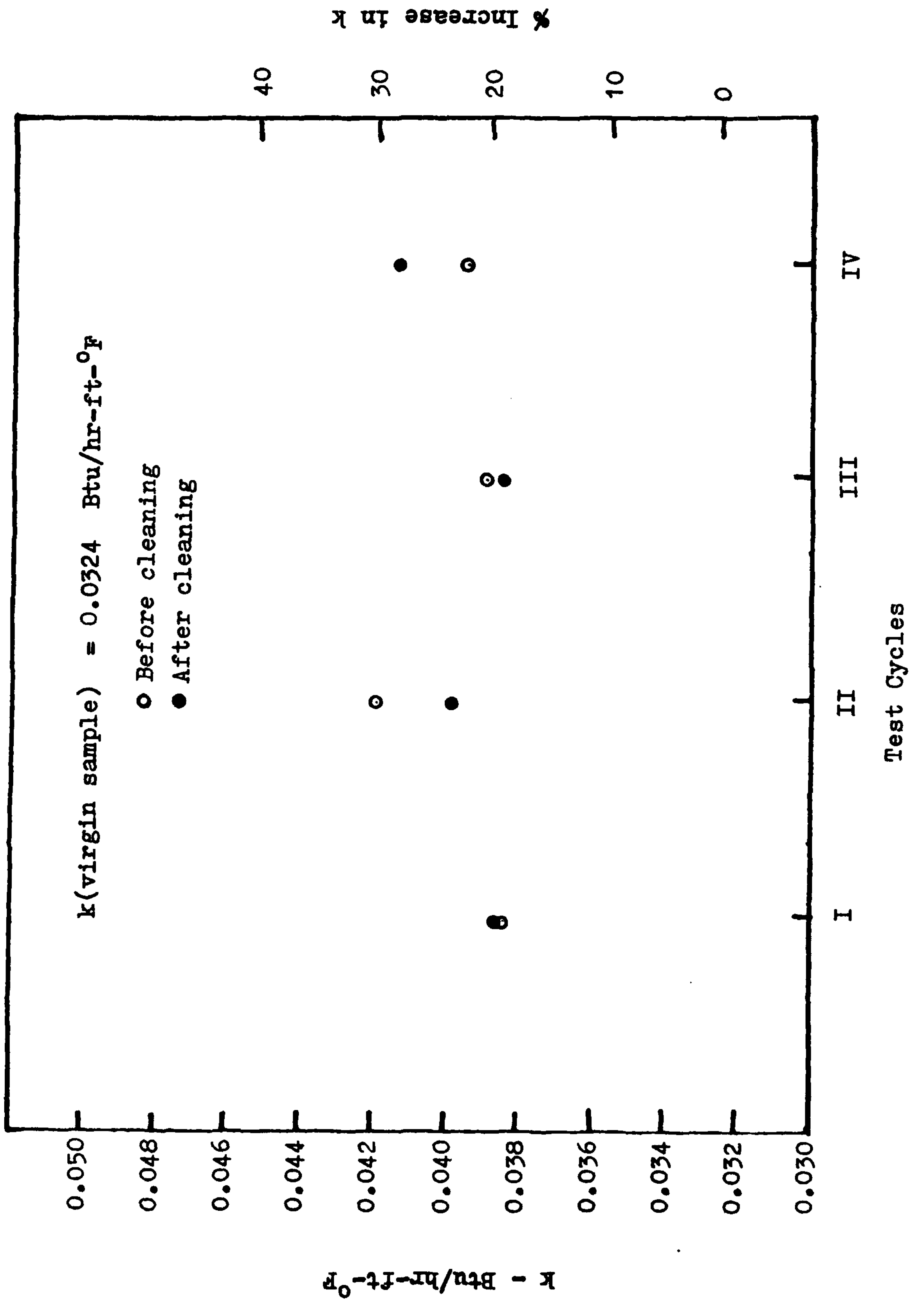


FIGURE 9 - k VERSUS TEST CYCLES

To anchor the foam sample and to apply the required tensile loading to it, a special wooden frame was constructed to fit inside a 15" X 24" X 6" deep test cell made of sheet metal (See Fig. 10). As shown in the figure, one edge of the sample, held in between two wooden strips, was anchored to the wooden frame, while at the opposite edge of the sample (which was also held between two wooden strips) a tensile load was applied via a string and pulley arrangement.

In real-life situations, the degree of stretch associated with the wearing of the suit by a diver depends, among other factors, upon the diver himself and on the specific use of the diving suit. In the present tests, two loads (3 lbs and 6 lbs) corresponding to 0.5 psi and 1 psi loading over the cross sectional area of the sample were used. For each loading, the tests were also repeated in order to evaluate the effects of the <u>duration</u> of immersion under a given load and of the cycle of applying and relieving the load. The results are tabulated in Table V. The results show that the sample undergoes a total elongation of $\approx$2% in the direction of loading by the end of four (4) test cycles, two cycles at each loading; whereas, the observed increases in the sample density due to absorption of the test fluid is $\approx$15%. The thermal conductivities and the percent changes in k for each test loading and cycle are shown in Figure 11. The data show a general increase of about 25% in k for all the tests.

It can be seen from the results of the oil-suit-material interaction test series and the variable-temperature test series that the increase in the thermal conductivity as well as density therein are essentially of the same order of magnitude as those found herein. The foregoing result appears to imply that the suit material absorbs a certain amount of oil even when it is under no loading and that the changes in thermal conductivity are associated with this absorbed oil. Loading the sample, at least in the ranges used herein, causes neither further absorption of oil nor a further increase in the thermal conductivity.

<u>Dynamic Tests</u>

The purpose of this test series was to examine the effects on the suit-material sample of dynamic loads due to repeated entries of the diver into the water-oil mixture under the "worst case" scenario. The "worst case" test fluid, as was determined from the results of

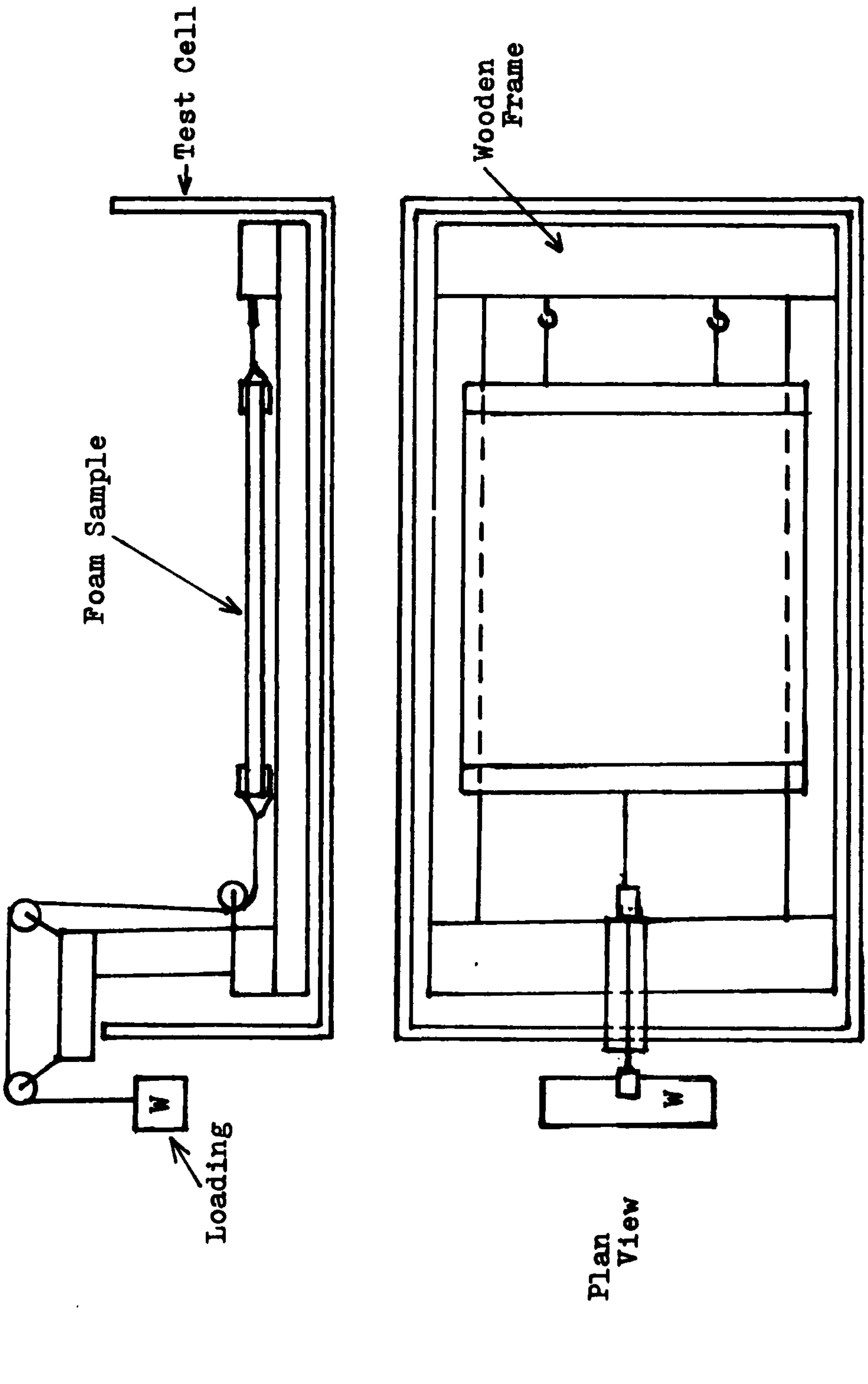


FIGURE 10 - STRETCH TEST SET-UP

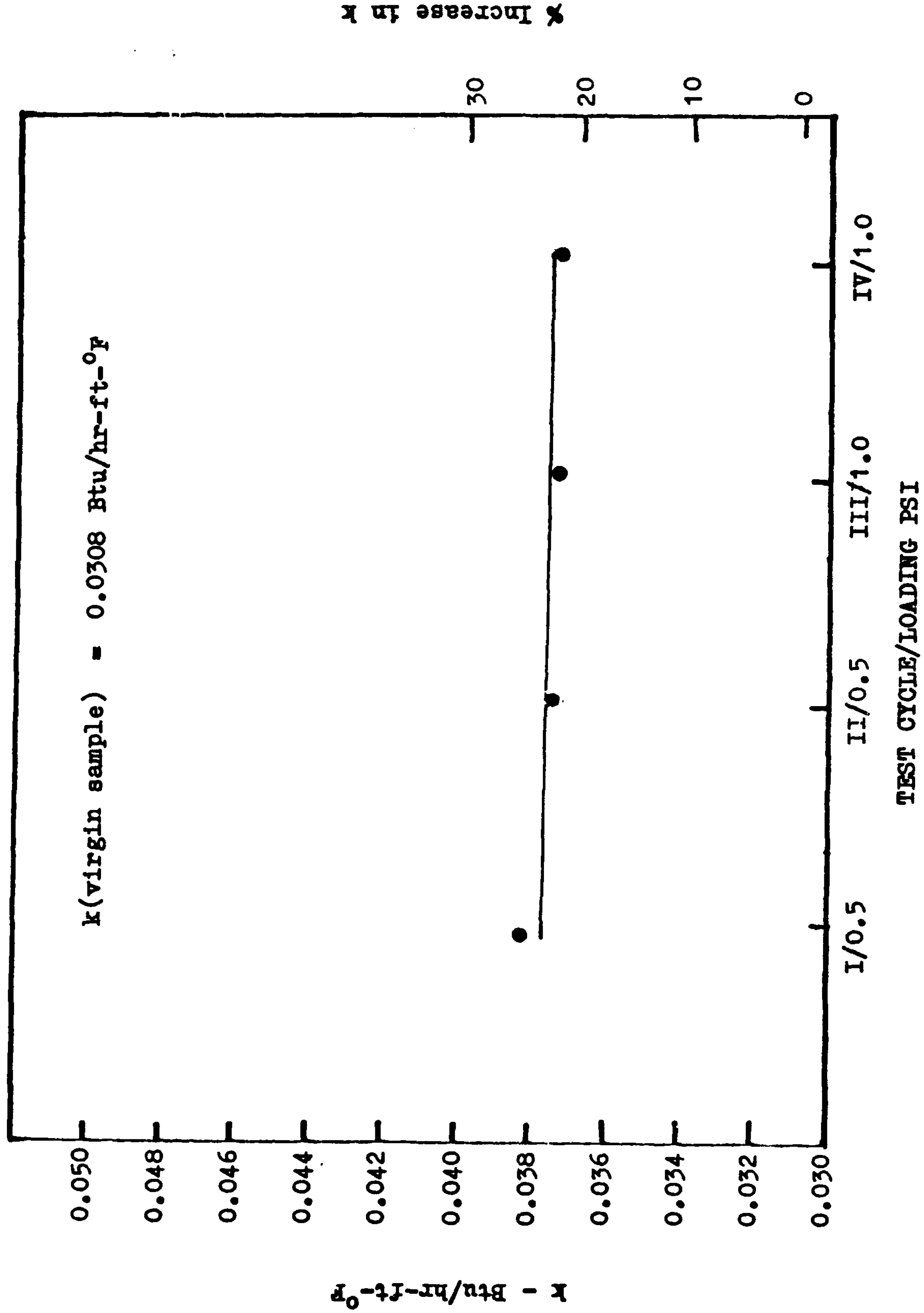
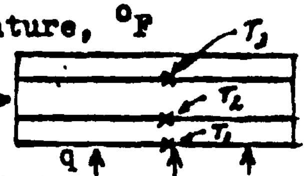


FIGURE 11 - k VERSUS TEST LOADINGS

TABLE 5 RESULTS OF STRETCH TESTS

Test temperature: $0^{o}C$ Test Fluid: #6 Fuel Oil + 35‰ salt water						
Tensile loading/Test cycle		Virgin Sample	0.5psi/I	0.5psi/II	1.0psi/III	1.0psi/IV
Sample thickness, t inches		0.265	-	-	-	0.265
Length of markings - d inches Stretch direction/ $\perp$ direction		6/6	6/6	$6\frac{1}{16}$/6	$6\frac{1}{16}$/6	$6\frac{1}{8}$/6
Water displacement, (net) D cc		395	455	455	460	465
Temperature, ^{o}F Foam 	T_1	125.4	117.3	125.0	120.1	127.3
		126.1	118.1	125.7	120.7	128.1
	T_2	118.8	110.4	118.3	113.3	120.6
		119.6	111.1	119.1	114.0	121.4
	T_3	86.4	82.4	91.3	85.1	93.5
		86.8	82.9	91.6	85.6	93.8
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.00/0.00	0.0104/0.00	0.0104/0.00	0.0208/0.00
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_S d_L}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	0.00	0.010	0.010	0.021
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.152	0.152	0.165	0.177
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.152	0.142	0.155	0.156
Thermal Conduct. k, Btu/hr-ft-^{o}F		0.0308	0.0384	0.0376	0.0375	0.0374
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$		-	0.247	0.221	0.218	0.214
Insulation in CLO units		0.818	0.656	0.670	0.672	0.674

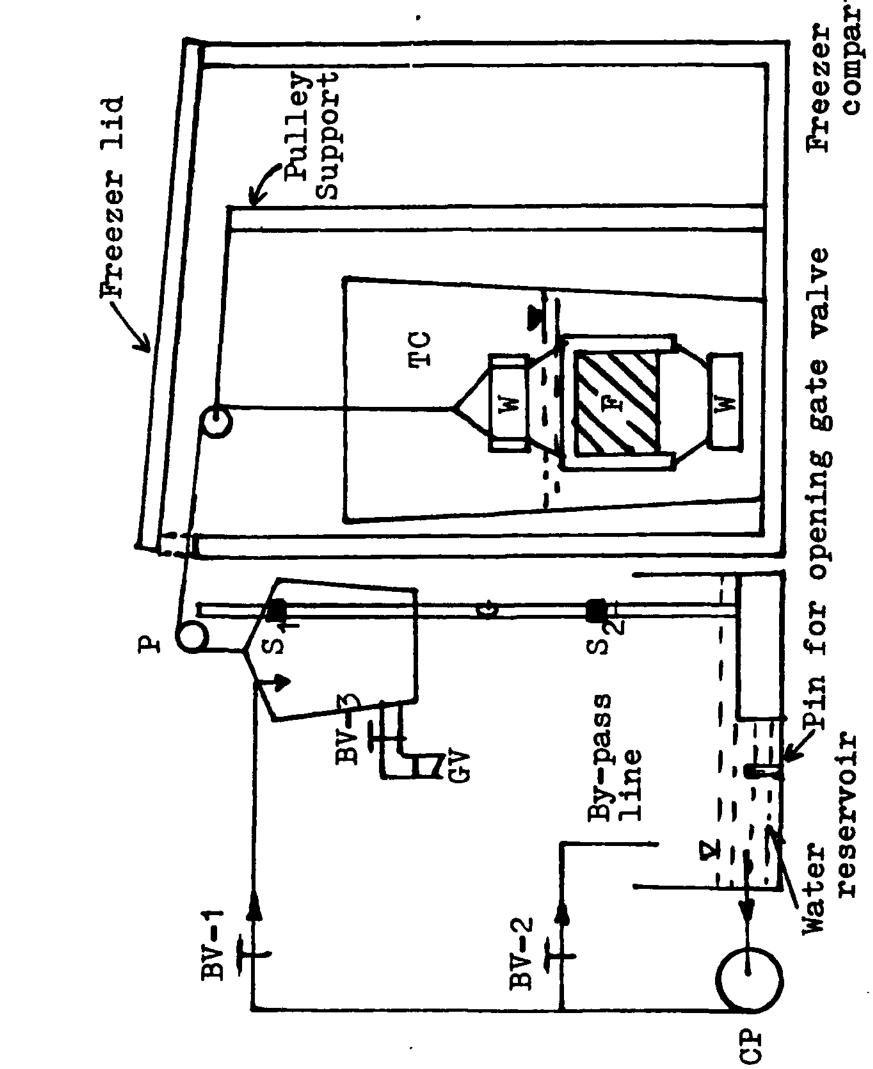
NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.

the variable-temperature tests, consisted of a mixture of #6 Fuel oil and 35% salt water in a 50:50 ratio by volume, and the test temperature was chosen as $0^{o}C$.*

A necessary prerequisite to the performance of the tests was the development and construction of a mechanism which could automatically raise the suit-material sample out of, and reinsert it into, the test fluid in a cyclic fashion, with the period of the cycle being controllable. Initially we had envisioned that the foregoing task could be accomplished by a small electric motor, along with appropriate gears, cams and linkages. However, because of the very viscous nature of the test fluid at $0^{o}C$, and because of the fact that it took a considerable force to insert the sample into the test fluid rapidly, it soon became apparent that any rotating mechanism of the type just mentioned would not only require considerable power for operation, but would also be subjected to very severe nonuniform, unsteady torque loads. Therefore a relatively simple, albeit versatile, alternative technique was developed.

It was clear that an automatic up-and-down movement, which could be used to raise and lower the suit-material sample, could be achieved with a simple pulley arrangement in which the (appropriately weighted) suit-material sample was at one end and a variable counterweight was at the other end, provided that a technique could be developed to appropriately vary the counterweight. A schematic of the mechanism that was eventually developed is shown in Fig. 12. As shown in the figure, the variable counterweight consisted simply of a plastic bucket into which water (from a small reservoir) was continuously pumped by means of a small circulating pump. The rate at which water was introduced into the bucket could be controlled by the bypass line and by the ball valves #1 and #2, as shown in the figure. A drain pipe and a gate valve were attached to the bottom of the bucket, and an upward force on the "gate" was used to open the valve at a desired instant and to drain the water out of the bucket at a faster rate than that at which it was being pumped in. The rate of draining through

*It may be noted herein that at subzero temperatures some of the water, which eventaully always separates from the oil-water mixture, freezes, so that it is not possible to readily withdraw the sample or reinsert the sample into the test fluid. Thus a test temperature of $0^{o}C$ was chosen as the lowest possible value.



CP Circulating pump
BV Ball valve
GV Gate valve
P Pulleys
W Weights
F Foam Sample in pressure seal
TC Test container with oil-water mixture
G Guide rod with friction lugs S_1 and S_2

FIGURE 12 - SCHEMATIC OF THE TEST SET-UP FOR THE DYNAMIC TESTS

the gate valve could itself be controlled by adjusting the ball valve #3 shown in the figure.

The operation of the system is as follows. At the start of a raising-and-lowering cycle, the suit-material sample (mounted in a pressure seal of the type already described) is submerged within the test fluid, while the bucket (which, at this point, is nearly empty) is at the top of its stroke. As the water continues to be pumped into the bucket, it progressively gets heavier, and eventually its weight exceeds the weight at the other end plus any frictional force that may be present. At this point, the bucket moves downward, raising the suit-material sample out of the test fluid in the process. At the bottom of the stroke, a small lug mounted on the bottom of the water reservoir engages the gate valve and begins to drain the water out of the bucket. When the weight of the bucket becomes sufficiently lower than the weight at the other end, it moves up and in the process reimmerses the suit-material sample back into the test fluid. The cycle then continues.

While the aforementioned simple procedure worked quite satisfactorily with room-temperature water as the test fluid, it did <u>not</u> work satisfactorily with the oil-water mixture at $0^{o}C$, since the large viscous forces made the up-and-down movement of the weight system very sluggish. A slight modification of the system, however, was sufficient to yield satisfactory operation. First, a guide rod which passes through a hole in the upper lip of the bucket was provided, as shown in Fig. 12. Second, "friction lugs" made of O-rings and electrical tape, and which were slightly oversized compared to the size of the hole in the lip of the bucket, were provided on the rod at locations corresponding to the top and bottom of the stroke of the bucket motion. At the beginning of a cycle, the lip of the bucket is located <u>above</u> the upper friction lug. Thus as the bucket begins to fill, it is held in place until its weight is sufficient to overcome not only the weight at the other end, but also the frictional resistance of the lug. When the foregoing critical weight is exceeded, the bucket "breaks through" the lug and "falls" rapidly to the bottom of its stroke, also breaking through past the lower friction lug in the process. At this point, the gate valve opens and the bucket begins to empty; however, it is held in place by the lower friction lug until the bucket empties sufficiently and until the now larger weight at the other end can overcome the frictional resistance of the lug. The bucket then rapidly moves upward, also breaking through the upper friction lug, and in the process lowers the suit-material sample into the test fluid. The cycle is then repeated. It should be noted that the aforementioned modification also makes the up-down cycle more nearly akin to a "square, saw-tooth" cycle than to a nearly sinusoidal cycle (as in the unmodified case).

Three consecutive, but separate, 5-hour tests were conducted at 8, 38 and 20 cycles per hour of raising and lowering of a sample into the test fluid (see Fig. 13). The test results are shown tabulated in Table 6. The results show that the sample undergoes an elongation of about 2%, while its thickness decreases by about 7%. The observed increases in the sample density due to absorption of the test fluid is about 25%. The values of the thermal conductivity, k, as well as the percent changes in k after each test cycle, are shown in Figure 14. The data show a general increase of about 30% in k at the end of the third test cycle.

Comparison of the present test results with those for the oil-suit-material-interaction test series and for the variable-temperature test series shows about the same order-of-magnitude increase in k in all cases, thus again suggesting that the primary reasons for the changes in k are associated more with the absorption of the oil by the foam rather than with dynamic loading due to its repeated immersion into the test fluid.

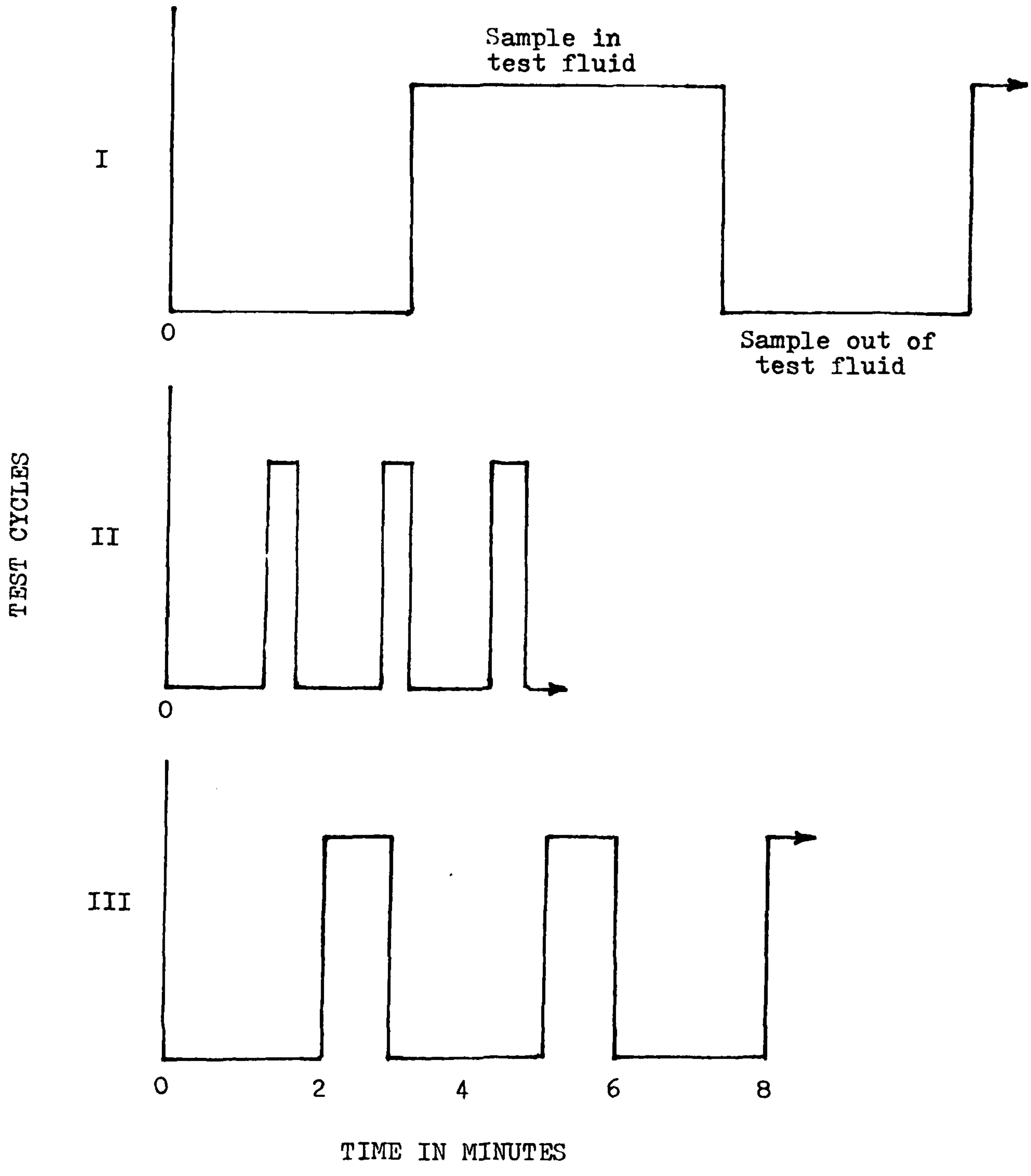


FIGURE 13 - TEST CYCLE PERIODS

TABLE 6 RESULTS OF DYNAMIC TESTS

Test temperature: $0^{o}C$		Test Fluid: #6 Fuel Oil + 35‰ salt water				
Test cycle/Impact frequency per hour		**Virgin Sample**	I/8	II/38	III/20	
Sample thickness, t inches		0.280	0.270	0.260	0.255	
Diameter of inscribed circle, d inches		$4\frac{3}{32}$	$4\frac{5}{32}$	$4\frac{3}{16}$	$4\frac{3}{16}$	
Water displacement, (net) D cc		175	200	205	210	
Temperature, ^{o}F **Foam** → 	T_1	114.6	112.9	116.8	114.8	
		114.9	113.5	117.4	115.4	
	T_2	108.3	106.2	109.9	107.4	
		108.7	106.9	110.5	108.0	
	T_3	85.8	88.2	92.5	88.9	
		86.2	88.8	93.1	89.4	
Elongation, $\frac{\Delta d}{d} = \frac{d_2}{d_1} - 1$		-	0.015	0.023	0.023	
Volume Change $\frac{\Delta V}{V} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{t_2}{t_1}\right) - 1$		-	-0.006	-0.0284	-0.047	
Mass Change $\frac{\Delta m}{m} = \frac{D_2}{D_1} - 1$		-	0.143	0.171	0.200	
Density Change $\frac{\Delta \rho}{\rho} = \frac{\Delta m}{m} - \frac{\Delta V}{V}$		-	0.149	0.199	0.247	
Thermal Conduct. k, Btu/hr-ft-^{o}F		0.0241	0.0290	0.0311	0.0309	
Thermal Conduct. Change $\frac{k_2}{k_1} - 1$			0.224	0.291	0.282	
Insulation in CLO units		1.046	0.869	0.810	0.816	

NOTE: Subscripts 1 and 2 refer to virgin sample and after test conditions.

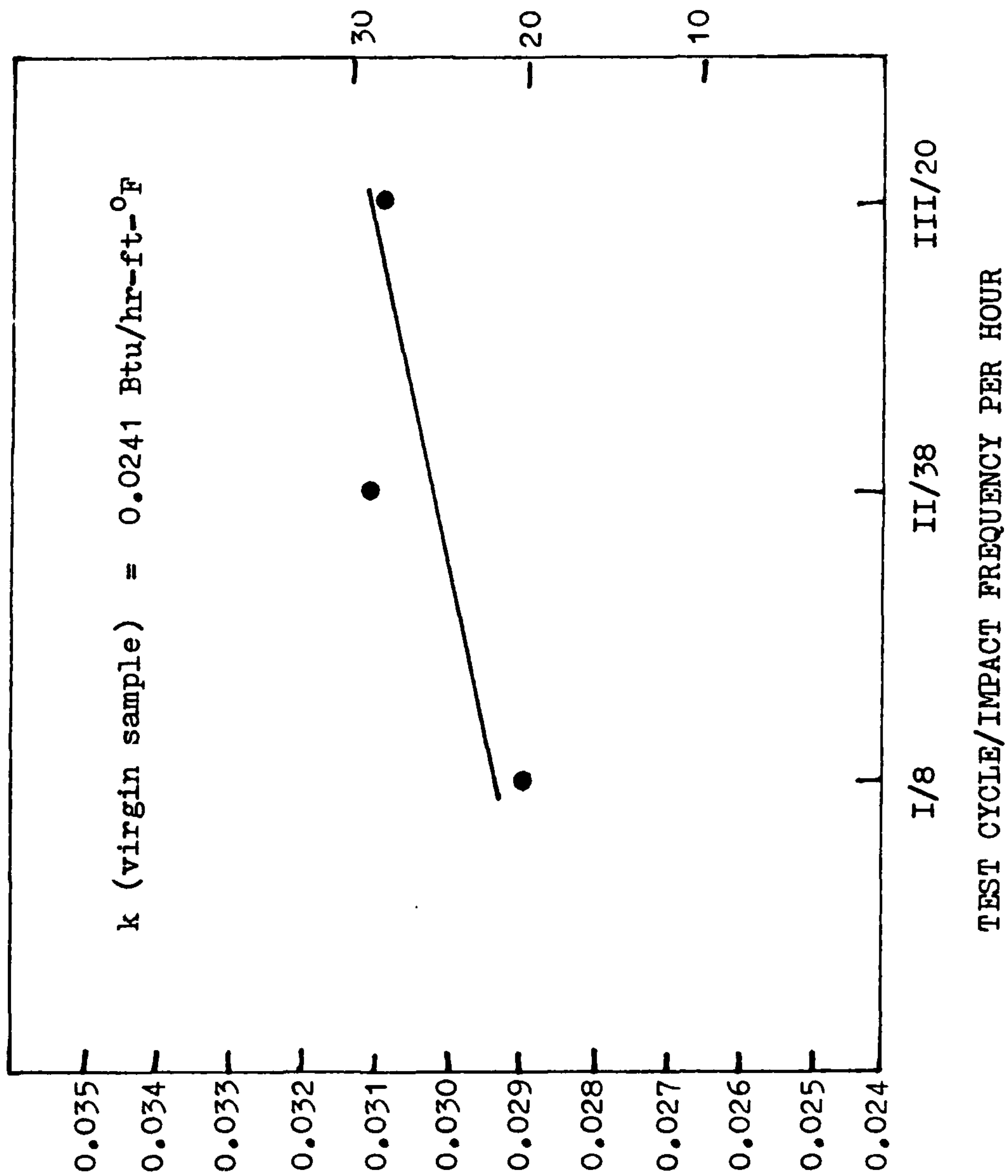


FIGURE 14 - k VERSUS IMPACT FREQUENCY

V. CONCLUDING REMARKS AND RECOMMENDATIONS

At present very little information exists on the degreee of thermal protection provided to divers by polar-diving-suit material in the confined presence of frigid temperatures, saline water and oils. The present study has involved certain relatively simple series of laboratory tests on small samples of the suit material, in which the changes in the physical and thermal properties of the material due to its exposure to a wide variety of oil-water mixtures and temperatures have been assessed, according to a prespecified test plan formulated by the U. S. Coast Guard. The test results show that while the suit material performs quite adequately under most conditions, it does absorb some oil (or, more correctly, some of the oil-water mixture). The absorbed oil appears to be confined to the outer nylon fabric and perhaps also to the uppermost foam layers, since no traces of oil were ever evident either on the (unexposed) inside surfaces of the foam or on its edges.

The absorbed oil could not be removed totally by gravity draining, by expression, by patting with absorbent paper toweling, or even by washing with commonly available detergents. The absorbed oil leads to an increase in the density of the foam as well as in the thermal conductivity of the suit material, the actual values being dependent on a number of factors such as the oil in question, the test temperature, the period of immersion and so on. One obvious way of preventing the absorption of oil by the outer nylon fabric lining may be to treat it with an appropriate oleophobic chemical.

In the present program, a number of different oils and a number of different test conditions have been used. Since the results have already been summarized in the tables and in the figures given in the body of the report, there is no need to discuss them again herein. It is relevant to note, however, that the "typical" maximum value of the changes in thermal conductivity that were measured in the tests was of the order of thirty percent (see, for example, Table 3.10, page 36), which corresponds to a reduction in thermal protection of about 0.2 CLO units.

The present study and its results should be considered to be preliminary ones, since there are some uncertainties and ambiguities in both the manner in which the tests were conducted as well as in the test plan itself. For example, in the tests, after the suit-material samples were removed from the test oils, the superficial as well as some of the absorbed oil was removed by first gravity draining, and then by scraping with a knife-edge scraper and also by toweling-off with absorbent paper toweling. Although we tried to be consistent in the degree of oil removed (before the measurements were made) in all the tests, the degree of oil removal is subjective. For instance, had we not used scraping and toweling-off and had we relied on gravity drainage alone, the amount of absorbed oil reported would have been considerably higher (since at the lower temperatures the more viscous oils do not drain off readily).

Also it is unclear as to how representative the 50-50 oil-water emulsions that were used in the present test are of real-life situations. Firstly, although the emulsions had been formed in a high speed blender, they tended to deemulsify during the tests. Secondly, while a diver entering the water through an opening in the ice cover may first be exposed to a large concentration of oil near the bottom surface of the ice, he will probably be operating for the major part of his dive in a zone containing mostly water. Thus while the suit-material may absorb some oil initially, it will then be exposed mainly to water, so that a more respresentative test may have been one in which the suit materials were <u>first</u> immersed in oil, and then tested in <u>water</u> at the specified temperatures and for specified intervals

Also, while in our tests the samples were kept at low temperatures during the tests, during the measurements they were not. It is unclear, for example, as to whether the act of removing the samples from the test fluids, removing the superficial and absorbed oil and placing them in the TCM Box (at nearly room temperature) has any effect on the actual changes in the thermal conductivity. Clearly, in-situ measurements in which the changes in thermal conductivity are measured by using thermocouples when the test samples are still immersed and are still at the specified temperature would have been better.

The foregoing aspect may be especially important when viewed in relation to another aspect. In the tests, it was assured that only the outside surface of the suit material will be exposed to the oil-water mixtures by folding the samples and by pressure sealing the edges. However, since the entire sample was immersed in the test fluid at the controlled temperature, the inside and outside surfaces were subjected to essentially the same temperature. On the other hand, in actual use, the inside of the suit material will be at a temperature close to that of the environment. In other words, while in actual use there will be a temperature gradient across the foam, no such gradient was present in the tests. Since heat and mass transfer are closely related, it is unclear as to how the absence of a temperature gradient affects the amount of oil that is absorbed by the suit material. Thus a more representative test may have been one in which the inside surface of the suit material is exposed to a controlled temperature typical of a diver's body, and the outside is exposed to the test fluid at the controlled temperature of the environment, with "in-situ" measurements being made with thermocouples placed on both surfaces of the suit material.

We have pointed out the foregoing aspects herein to emphasize that the problem of defining the changes in thermal properties of polar-suit materials due to their combined exposure to frigid temperatures, saline water and oils is by no means an easy one. On the other hand, we believe that the relatively simple program we have described in the present report is a good preliminary study which provides useful estimates; but it is by no means the last word on the subject.